ABSTRACT

Title of Thesis: FLAMMABILITY CHARACTERISTICS OF WATER-BASED POLYCRYLIC AND OIL-BASED POLYURETHANE COATED OAK VENEER PLYWOOD SAMPLES SUBJECTED TO INCIDENT HEAT FLUXES

Sarah Elizabeth Thompson, Master of Science, 2005

Thesis Directed by: Dr. Frederick W. Mowrer, Associate Professor, Department of Fire Protection Engineering

The flammability characteristics of oak veneer plywood were evaluated in the Cone Calorimeter. Samples of 6.35 mm (1/4 in.) thick and 19.05 mm (3/4 in.) thick oak veneer plywood were coated with 3, 6, and 9 coats of either oil-based polyurethane or water-based polycrylic clear finishes and tested at incident heat fluxes of 35, 50, and 75 kW/m^2 along with uncoated samples. Both the type of finish and the number of coatings were found to influence the ignition time, the measured peak heat release rate, and the minimum flux for ignition of the samples. The ignition times for the coated samples were 2 to 3 times lower than the unfinished samples. Predicted times to ignition differed by a factor of 2 to 3 from the measured values (with the exception of the samples with nine coats of finish.) The predicted ignition temperatures differed by as much as 100 ºC from the measured temperatures. The Quintiere flammability parameter, *b*, was found to be positive for all testing scenarios, suggesting a propensity for flame spread at the incident heat fluxes evaluated.

FLAMMABILITY CHARACTERISTICS OF WATER-BASED POLYCRYLIC AND OIL-BASED POLYURETHANE COATED OAK VENEER PLYWOOD SAMPLES SUBJECTED TO INCIDENT HEAT FLUXES

By

Sarah Elizabeth Thompson

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2005

Advisory Committee:

Professor Frederick W. Mowrer, Chair
Professor James A. Milke
Professor Peter B. Sunderland

ACKNOWLEDGEMENTS

This project would not have been possible without the financial support of the National Institute of Standards and Technology (NIST). The use of the cone calorimeter at the Bureau of Alcohol Tobacco Firearms and Explosives Fire Research Laboratory was generously provided for the completion of this project. Supplies provided by Piping Design Services (PDS) were greatly appreciated.

Disclaimer

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

b	flammability parameter (dimensionless)
c	specific heat (kJ/kgK)
h	heat transfer coefficient (kW/m^2K)
k	conductivity (kW/mK)
$k\rho c$	thermal inertia (kW^2s/m^4K^4)
m	mass (kg)
$\dot{q}$ ”	heat flux (kW/m^2)
Q	energy (kJ)
t	time (s)
T	temperature (°C or K)
v	flame spread rate (m/s)
x	flow coordinate direction
Δ	heating length (m)
Δh	change in enthalpy (kJ/kg)
ΔH_c	heat of combustion (kJ/kg)
L_v	latent heat of vaporization (kJ/kg)
ΔT	temperature rise above ambient (K)
α	absorptivity (-)
α	thermal diffusivity, $k/\rho c$ (m^2/s)
δ	heating depth (m)
δ_b	effective burning thickness (m)
ε	emissivity (-)
τ_b	dimensionless time, t/t_b
ρ	density (kg/m^3)
σ	Stefan Boltzmann constant (5.67×10^{-11} $kW/m^2 \cdot K^4$)
ϕ	flame heating parameter (kW^2/m^3)

Superscripts

.	per unit time
’	per unit length
”	per unit area

Subscripts

a	ambient
abs	absorbed
act	actual
b	burning duration
c	characteristic, convective
eff	effective
ext	external
f	flame
ig	ignition
inc	incident
k	conductive
max	maximum
net	net absorbed or lost
o	initial, ambient
r	radiative
s	surface

Chapter 1. INTRODUCTION

Plywood is a popular building material and its use ranges from furniture to house construction. There are many advantages of plywood: 1) Standard size (4 feet x 8 feet is the common size in the U.S.) 2) Low cost for the size 3) Strength and 4) Stability (warping and shrinkage is much less of a problem). Plywood is made by first generating a thin layer of wood in a continuous veneer sheet. Several layers of veneer are layered with the direction of the grain alternating between each layer. The layers are joined with an adhesive and the stack is heated and pressed to form a rigid panel. Because the grain direction of the layers of veneer alternates, the panel is extremely strong in all directions.

Cabinet grade plywood with nominal thickness of ¾ inch (19.05 mm) is commonly used for cabinetry and furniture, such as desks and bookcases. Plywood with a nominal thickness of ¼ inch (6.35 mm) is used for interior wall and ceiling finishes. Oak is a popular species for the surface veneer in both thickness applications. Wood stains and or protective clear finishes are commonly used to enhance the visual appeal and, in some cases, seal the plywood.

Since interior finishes represent a large surface over which flame can spread [1] there is a need to evaluate the flammability characteristics of interior finishes. Thus, the objective of this project is to determine the flammability characteristics of finished and unfinished oak veneer plywood with nominal thicknesses of ¼ inch and

¾ inch. The plywood samples were coated with 0, 3, 6, and 9 layers of oil-based polyurethane and water-based polycrylic clear finishes. These materials were tested in the cone calorimeter under imposed flux levels of 35, 50, and 75 kW/m^2. The cone calorimeter [2] was used to measure the heat release rate, mass loss rate, and time to sustained flaming. Additionally, the minimum flux for ignition and the temperature at ignition were measured. The results from all testing were used to evaluate the effective flammability properties of the finished and unfinished materials. The influence of the type and amount of finish was further characterized.

Historically, flame spread characteristics have been regulated in the U.S. using a comparative assessment per ASTM E84 (NFPA 255) using the Steiner Test Tunnel [3]. However, performance in the tunnel test does not always correlate with performance in the field. Efforts have been made to find better methods of evaluating and predicting the flammability characteristics of interior finishes. The cone calorimeter is now being used to study the combustibility of building materials. Recent usage of the cone calorimeter for purposes of studying the effects of finishing on flammability parameters has been reported [4, 5, 6]. McGraw and Mowrer [7] used the cone calorimeter to investigate the flammability characteristic of gypsum wallboard coated with varying coats of latex paint. In the study, no conclusion was made to directly relate the number of coats to the propensity for flame spread. Mowrer [5] further studied painted gypsum board and observed the effects of blistering on the flammability characteristics. This study found that blistering at the surface lead to a decrease in time to ignition by a factor of three to four. This reduction was attributed to blistering of the paint layer and its subsequent

behavior as a thermally thin material. More recently, Dreisbach [6] evaluated the flammability of painted concrete block exposed to an incident flux in the cone calorimeter. In this study, the calculated and measured values for effective thermal properties were found to differ by a factor of 2 or more, with the calculated values being higher. Based on the analysis of test results, it was determined that the standard methods used for evaluating effective material flammability properties yielded erroneous results for painted concrete blocks. A suggestion to find alternative methods for evaluating these properties was offered.

Mowrer [8] reviewed and analyzed the standard methods used to derive effective thermal properties of thermally thick materials based on bench-scale radiant exposure tests. The standard analytical methods for predicting surface temperature histories were found to be inaccurate because they either ignore heat losses from the surface or do not adequately account for the highly nonlinear reradiative surface heat loss term. Mowrer presented a method to determine more accurate values for the thermal inertia based on the effective values that are reported in the literature. It found that actual thermal inertias tend to be 1.3 to 2.7 times lower than the reported effective values for a wide range of conditions. This has the potential to significantly affect the predictions of flame spread models that rely on accurate thermal inertia values. This work extends this previous work by evaluating the effects of surface coatings on the flammability characteristics or oak veneer plywood.

Wood is a difficult material to characterize because of differences in moisture content from sample to sample, differences between specimens, grain

orientation, etc. Much research has been performed to determine what these effects have on the measured parameters. No literature has been found that discusses the effects that type and coating levels of interior finishes have on the thermal properties of wood. The cone calorimeter has been used to evaluate the effects of wood species, density, thickness, heated surface (radial, tangential or cross-section), and irradiance level on the time to ignition, mass loss rate, heat release rate and fire endurance time for various wood specimens [9]. This report found the second peak in the heat rate history to correspond to the time when the back face of the specimen reached 300 ºC. All specimens were dried and tested with moisture contents less than 3%. According to the report, the specific heat is said to be almost the same regardless of the wood species. The value is considered to be 1.25 kJ/kg-K [10]. All testing parameters were found to affect the combustibility of the dried wood specimens.

Quintiere and Spearpoint [11] also tested the effect of species, grain orientation and heat flux on the prediction of piloted ignition of wood in the cone calorimeter. It was reported that the thermal conductivity varies in wood with emittance, density, moisture content, temperature and the type of gas enclosed in the material. Thermal conductivity was found to increase significantly with increasing moisture content – approximately 1.3 times as high at 30% moisture content than at 10%. Here the specific heat is given as 1.36 kJ/kg-K. An equation for the specific heat for wood as a function of moisture content is given in the Wood Engineering Handbook. The report contains several models for determining the time to ignition based upon different assumption. The thermal inertias can by yield from all of the

presented methods, and based upon the equations, different values of kρc will be found for each one. The critical heat flux found from the intercept of $t_{ig}^{-1/2}$ against incident heat flux varied for species, from a low of 1.1 kW/m^2 for maple (across the grain) to 11.7 kW/m^2 for redwood and douglas fir (both along the grain). The literature values of critical flux for the various wood species ranged from 10.5 kW/m^2 to 14.0 kW/m^2. Theoretical apparent thermal inertias calculated using the Atreya and Abu-Zaid [12] ignition time model ranged from 0.22 (kW/m^2·K)^2·s for redwood along the grain to 10.91 (kW/m^2·K)^2·s for maple across the grain. The thermal inertia for red oak along the grain was 1.01 (kW/m^2·K)^2·s and 1.88 (kW/m^2·K)^2·s across the grain [11].

Fangrat, et al. [23] studied the relationship between heat of combustion, lignin content and burning weight loss for several wood composites (different types of plywood and particle board) in the cone calorimeter. The report found no statistically significant correlation of heat of combustion to lignin content. However, there was evidence of a correlation between lignin content to the burning weight loss of the samples, but further investigation was suggested.

Chapter 2. THEORETICAL CONSIDERATIONS

This chapter addresses the theory of ignition and flame spread on solid materials. The response of solid materials to incident heat fluxes involves complex physical and chemical processes and interactions. For engineering purposes, these processes are simplified. This chapter addresses these simplified engineering approximations. Determining accurate values of thermal inertia, ignition temperature, minimum flux for ignition, and the time to ignition are vital in predicting a materials performance in a fire. There are numerous models available to determine effective material properties. ASTM E1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*, presents the ignition theory most widely used for predicting the ignition of thermally thick solids [13]. It is generally considered the standard for the Lateral Ignition Flame Spread Test (LIFT) apparatus but the theory covered is independent of the testing apparatus. The theory assumes a semi-infinite solid.

2.1 Ignition Theory

Consider a thermally thick solid whose surface is exposed to a constant and uniform incident heat flux, $\alpha \dot{q}_i^{"}$, with convective and reradiative cooling at the surface. Assume that the surface cooling can be represented in terms of a constant total heat transfer coefficient, h_t. This scenario is represented in Figure 2.1. The analytical solution [14, 8] for this scenario can be expressed nondimensionally as:

$$\frac{\Delta T_s}{\Delta T_c} = 1 - \exp\left(\frac{t}{t_c}\right) erfc\left(\sqrt{\frac{t}{t_c}}\right) \tag{2.1}$$

Where $\Delta T_c \equiv \frac{\alpha \dot{q}_{inc}^{"}}{h_t}$ and $t_c \equiv \frac{k\rho c}{h_t^2}$.

The characteristic temperature rise at the surface, ΔT_c, represents the maximum surface temperature that would occur if there was no conduction into the material. The characteristic time, t_c, represents the ratio between the conduction of heat into the surface and the convection and reradiation of heat from the surface. Equation 2.1 assumes a constant total surface heat transfer coefficient, h_t, which is inaccurate because this term varies with time. The total surface heat transfer coefficient includes surface convection and reradiation losses from the surface:

$$h_t\left(T_s - T_o\right) = h_c\left(T_s - T_o\right) + \varepsilon\sigma\left(T_s^4 - T_o^4\right) \equiv h_c\left(T_s - T_o\right) + h_r\left(T_s - T_o\right) \tag{2.2}$$

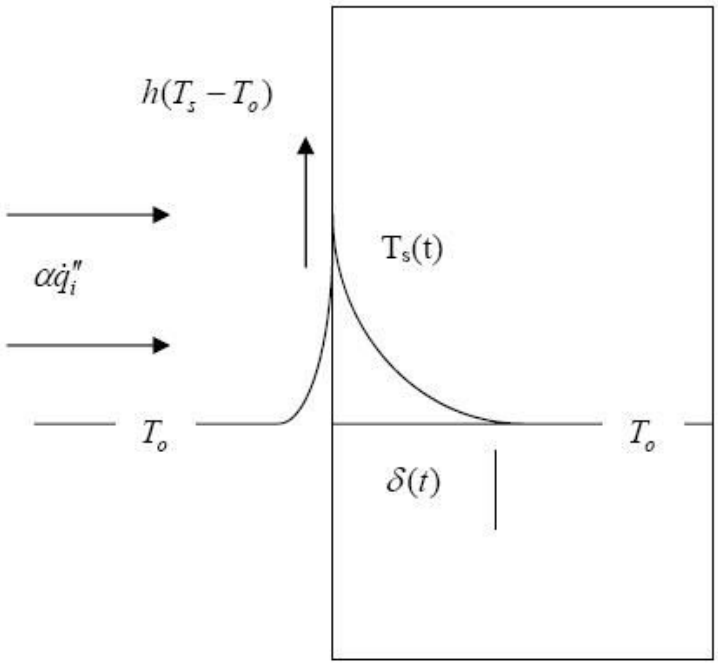

Figure 2.1 Schematic Diagram of Thermally Thick Heating Scenario [8]

The maximum theoretical value for the total heat transfer coefficient, $h_{t,max}$, can be evaluated by evaluating the energy balance at the surface under conditions where no conduction into the material occurs. This value can be expressed as:

$$\alpha\dot{q}''_{inc} = h_c\left(T_c - T_o\right) + \varepsilon\sigma\left(T_s^4 - T_o^4\right) \equiv h_{t,\max}\left(T_c - T_o\right) \tag{2.3}$$

The characteristic temperature is calculated as a function of the incident heat flux from Equation 2.3 using an iterative approach. Figure 2.2 shows the characteristic surface temperature and total heat transfer coefficient for a range of incident heat fluxes, based on a surface with perfect emissivity (ε = 1), a constant convective heat transfer coefficient value of 0.015 kW/m^2·K, and an ambient temperature of 20ºC.

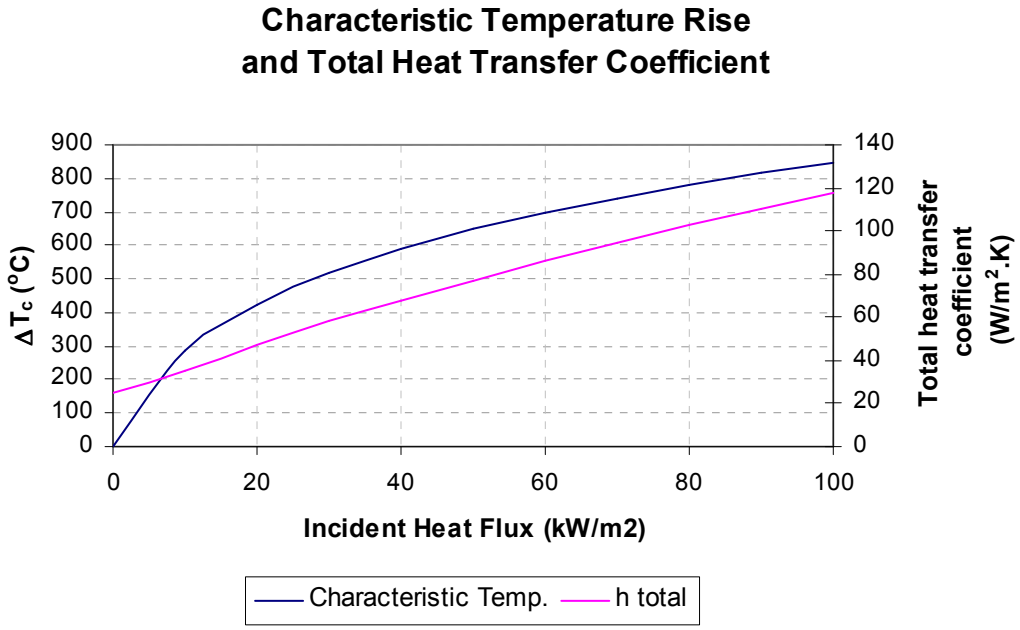

Figure 2.2 Characteristic Temperature Rise and Total Heat Transfer Coefficient as a Function of Incident Heat Flux

It has been shown [15] that time to ignition for thermally thick materials can be correlated by:

$$\frac{\dot{q}''_{\min,ig}}{\dot{q}''_{inc}} = F(t) = \begin{cases} m\sqrt{t}, t \le t^* \\ 1, t \ge t^* \end{cases} \tag{2.4}$$

where $\dot{q}''_{\min,ig}$ is the minimum flux for ignition and $\dot{q}''_{inc}$ is the incident heat flux. The function F(t) is the empirically determined counterpart to $1-\exp\left(\frac{t}{t_c}\right)erfc\left(\sqrt{\frac{t}{t_c}}\right)$.The left-hand side is plotted against the square root of time to ignition. The slope of the best fit line that passes through the origin is *m*. The term t^* refers to the intercept of the fit line with $\frac{\dot{q}''_{\min,ig}}{\dot{q}''_{inc}} = 1$. It is a characteristic time for the surface temperature to

reach steady state. The coefficient m can be related to the thermal inertia (kρc) which is the product of the thermal conductivity (k), the density (ρ), and the heat capacity (c) of the material. In this case kρc is an effective value which includes temperature effects, phase changes, and other effects [15].

The ignition temperature can be found from the following heat balance applied to the minimum flux condition:

$$\dot{q}''_{\min,ig} = \varepsilon\sigma\left(T_{ig}^4 - T_\infty^4\right) + h_c\left(T_{ig} - T_\infty\right) \tag{2.5}$$

where h_c is 0.01 kW/m^2·K for the cone calorimeter and T_∞ is the ambient temperature (assumed 20 ºC). In Equation 2.5 T_{ig} and T_∞ must be expressed in Kelvin. For high heat fluxes, the time to ignition can be approximately expressed as:

$$t_{ig} = k\rho c\left(\frac{\pi}{4}\right)\left(\frac{T_{ig} - T_\infty}{\dot{q}''_{net}}\right)^2 \tag{2.6}$$

where $\dot{q}''_{net} = \left(\dot{q}''_{inc} - \dot{q}''_{\min}\right)$. From Equation 2.6, it can be seen how kρc, T_{ig}, and $\dot{q}''_{inc}$ influence the time to ignition. In this model the chemistry of the material is all contained in T_{ig}. Equation 2.6 can be rearranged to yield the thermal inertia:

$$\left(k\rho c\right)_{eff} = t_{ig}\left(\frac{4}{\pi}\right)\left(\frac{\dot{q}''_{net}}{T_{ig} - T_\infty}\right)^2 \tag{2.7}$$

The aforementioned approach to determining the surface temperature rise ignores conduction into the material on the surface energy balance equation and effectively overestimates the actual ignition temperature. There are numerous alternatives to the ASTM E1321 approach. However, it is not the purpose of this paper to compare alternative methods.

2.2 Flame Spread

This work focuses only on the potential for concurrent or wind-aided flame spread because, in general, wind-aided flame spread presents greater hazard than opposed flame spread. This is also consistent with previous work on the flammability of coated surfaces [6]. The flame spread model developed by Saito et al. [20] has been applied to the evaluation of textile wall coverings adhered to gypsum wallboard [16] and latex- and oil-based painted gypsum wallboard [4, 5]. This model will hereafter be referred to as " the Quintiere model." The Quintiere model describes the potential for flame spread in terms of the ignition and burnout of surface elements as they are subjected to flame and externally imposed heat fluxes.

The Quintiere model introduces the dimensionless "flammability parameter," b, defined as:

$$b \equiv k_f \dot{Q}'' - \left(t_{ig} \Big/ t_b \right) - 1 \tag{2.8}$$

where the flame length parameter, k_f, is typically considered to have the value of 0.01 m^2/kW, assuming that the flame length is linearly related to the heat release rate. The heat release rate per unit area $\dot{Q}''$, is generally considered to be the peak heat release rate per unit area (PHRPUA), for the material and is obtained from testing in the Cone Calorimeter. From heat transfer theory for a semi-infinite solid with no convective or reradiative cooling at the surface, the time to ignition, t_{ig}, is

typically approximated in terms of Equation 2.6. The burning duration, t_b, is usually approximated as:

$$t_b = \frac{Q''}{\dot{Q}''} \tag{2.9}$$

for materials that produce only one peak along a heat release rate per unit area (HRRPUA) versus time curve. However, since the samples tested for this project produce two peaks on the HRRPUA versus time curve, another method must be utilized to determine the burning duration. The method used to analyze the data for this report required drawing a horizontal line across the HRRPUA time history plot at 100 kW/m^2. The time where the horizontal line first intersects the HRRPUA curve is considered t_1. The time where the heat release rate goes down to 100 kW/m^2 for the last time on the HRRPUA time curve is, t_2. It follows that:

$$t_b = t_2 - t_1 . \tag{2.10}$$

This method is illustrated in Figure 2.3.

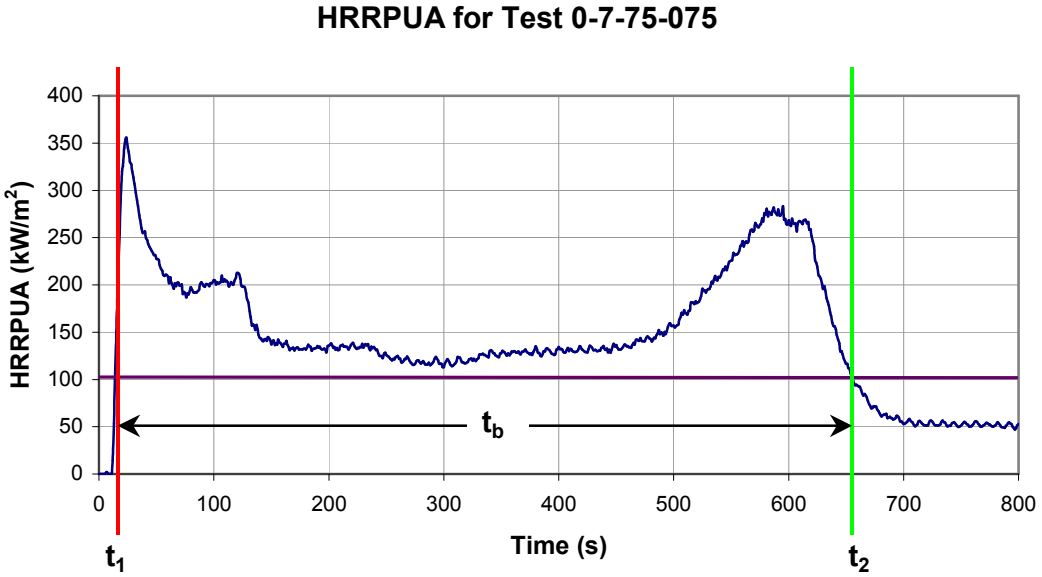

Figure 2.3 Determining the Burning Duration From the HRRPUA Time Plot

Before a fire can spread, the energy released by the fuel must be great enough and the duration of release must be long enough to ensure that enough heat is generated and transferred to an adjacent material to cause ignition. If the burning duration is long enough and the heat release rate is high enough, the b number would be greater than zero and flame spread is likely to occur. Based upon the Quintiere model, if the converse occurs, then flame spread is unlikely.

Chapter 3. EXPERIMENTAL PROCEDURE

3.1 Pre-Coating Measurements

Approximately 250 samples of 6.35 mm (¼ in.) and 19.05 mm (¾ in.) thick oak veneer plywood were cut into 100 mm (4 in.) square pieces from sheets of plywood that were purchased at a local building supply store. Measurements of sample mass, thickness and surface area were made prior to coating.

The surface area for the ¼ in. thick samples ranged from 101.51 cm^2 to 104.04 cm^2 with an average of 103.09 cm^2. The surface area for the ¾ in. thick samples ranged from 100.00 cm^2 to 105.06 cm^2 with an average of 102.22 cm^2. The measured surface areas for all samples are presented in Figure 3.1.

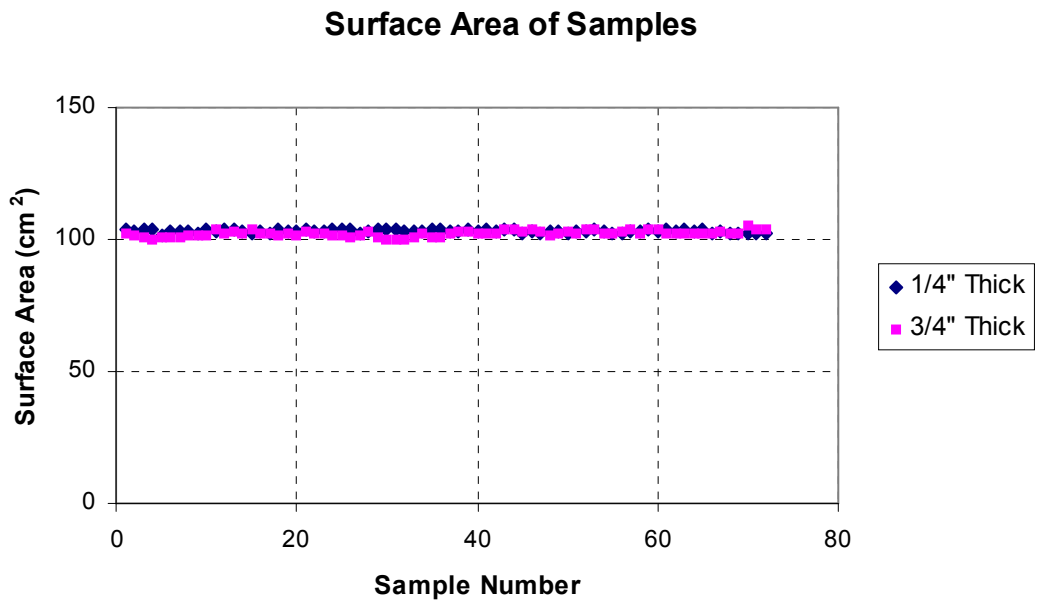

Figure 3.1 Surface Area of Samples

Sample thicknesses were measured with a vernier caliper. The thickness for the ¼ in. (nominal) thick samples ranged from 5.15 mm to 5.69 mm with an average of 5.40 mm. The thickness for the ¾ in. (nominal) thick samples ranged from 18.00 to 19.18 mm with an average of 18.63 mm.

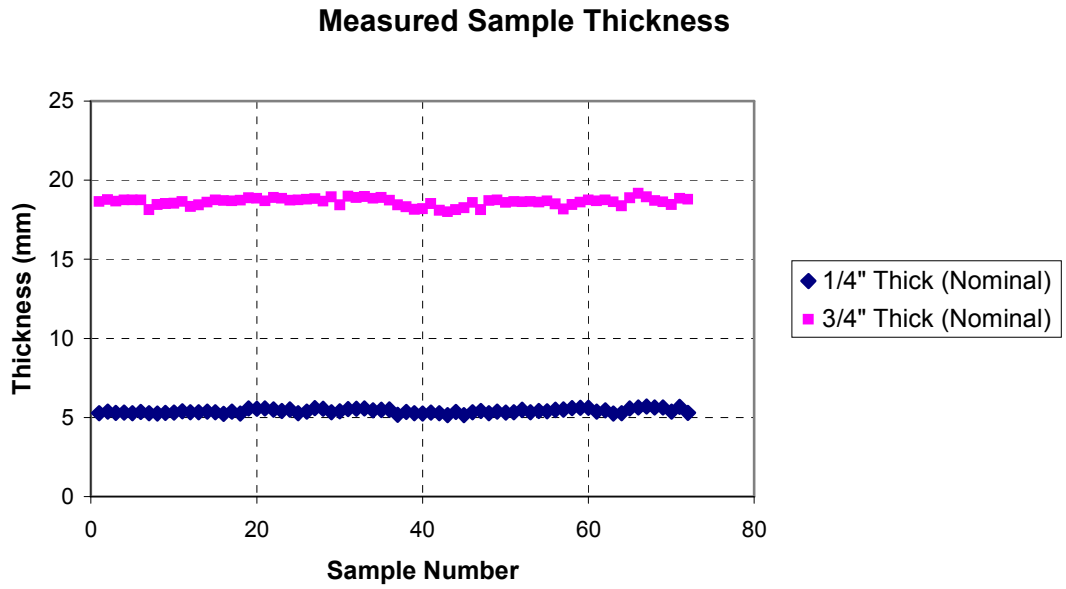

Figure 3.2 Measured Thickness of Samples

The average density of the ¼ in. nominally thick samples was found to be 520.38 kg/m^3, with a minimum of 460.00 kg/m^3 and a maximum of 587.12 kg/m^3. The average density of the ¾ in. nominally thick samples was found to be 566.28 kg/m^3, with a minimum of 532.52 kg/m^3 and a maximum of 604.84 kg/m^3. On average the ¾ in. plywood was found to be denser than the ¼ in. plywood. The measured densities for both plywood thicknesses encompass the reported value of density for oak. Reported material properties for oak and pine are presented in Table 3.1.

Table 3.1 Material Properties from SFPE Handbook [17]

Material	k (W/mºC)	ρ (kg/m^3)	c (kJ/kgºC)	α (m^2/s)
Oak	0.166	540	2.4	1.28 x 10^{-7}
Pine	0.147	640	2.8	0.82 x 10^{-7}

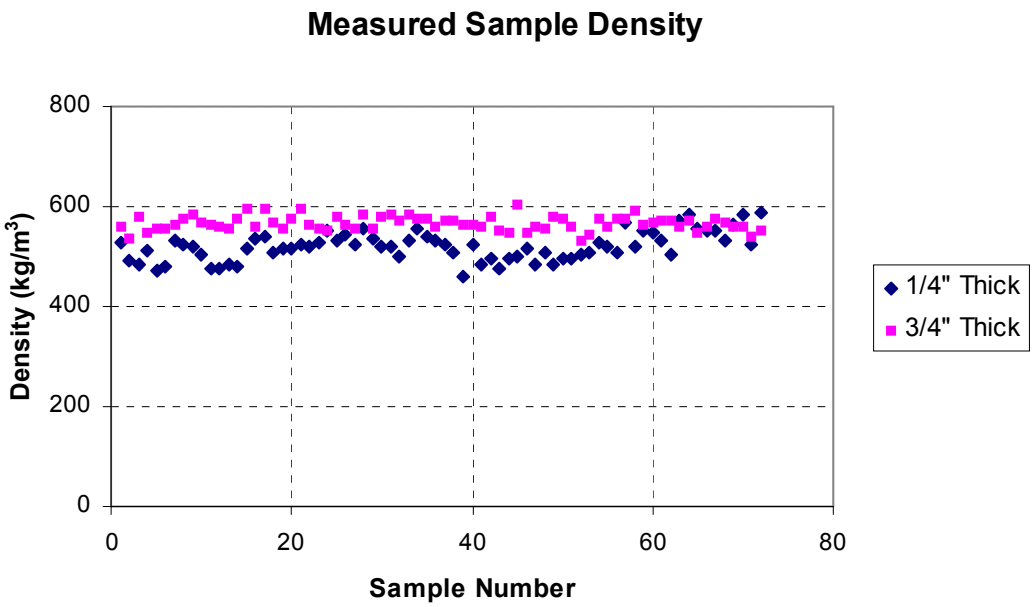

Figure 3.3 Measured Density of Samples

In order to determine the moisture content (MC), five samples of each thickness were weighed and then placed in a THELCO oven set to 124ºC. This temperature was chosen because it was above the boiling point of water (100ºC) but below the thermal decomposition temperature. After a period of 48 hours the samples were removed from the oven and placed in a closed container that contained a drying agent (Drierite). The samples remained in the desiccator until

cool enough to weigh. Moisture content in wood is usually calculated as a percentage of the oven dry weight by the formula:

$$MC = \left(\frac{OriginalWeight - DryWeight}{DryWeight} \right) 100\% \tag{3.1}$$

The moisture content is expressed as a percentage of "dry basis," signifying that the basis for the percentage is the dry weight at which all of the bound water has been driven off [18]. The moisture content in wood is not uniformly distributed – wood is often drier or wetter at its surface than its interior. Surface layers, which control ignition and flame spread, respond much faster to changes in atmospheric conditions than the interior; thus, bulk moisture content measurement must be considered with this fact in mind. Small variations in the percent moisture content have very little influence on the ignitability and heat release of wood.

It was determined that the ¾ in. samples lost more mass from drying than the ¼ in. samples. However the ¼ in. samples contained a greater percentage of moisture as found when dividing the mass loss by the total initial mass. The moisture content results for both thicknesses of plywood are summarized in Table 3.2.

Table 3.2 Sample Moisture Content

Thickness	Measurement	MAX	MIN	AVG	STDEV
1/4"	Mass Loss (g)	2.75	2.25	2.49	0.185
3/4"	Mass Loss (g)	7.00	6.55	6.81	0.195
1/4"	Percent Moisture	11.83	10.14	10.87	0.622
3/4"	Percent Moisture	9.19	9.05	9.11	0.068

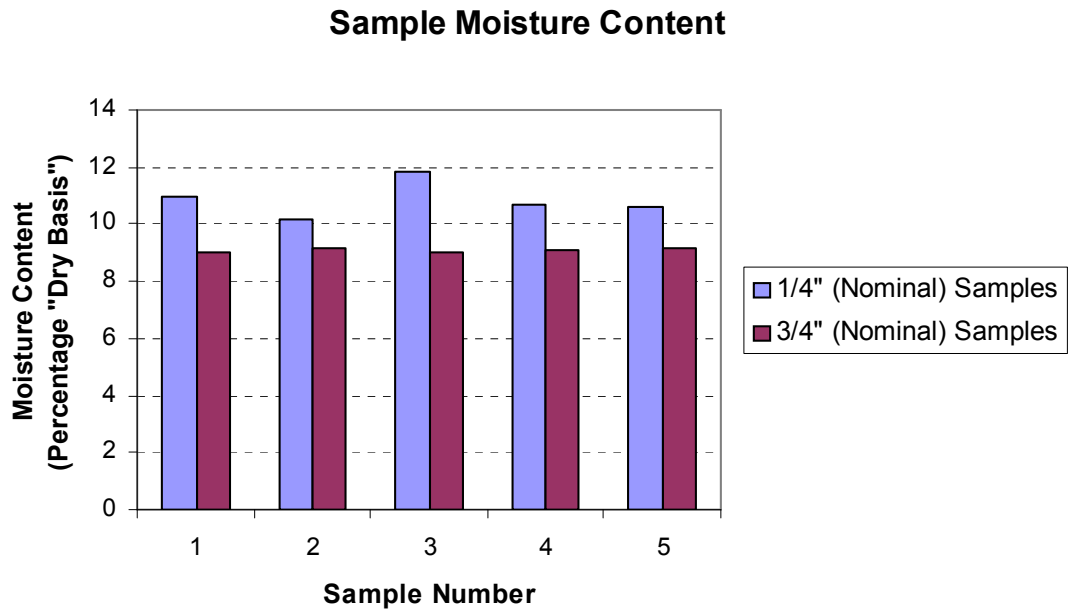

Figure 3.4 Moisture Content (Dry Basis) in Samples

3.2 Sample Preparation

After the uncoated samples were dried and weighed, the samples were prepared for testing. Six of the ¼ in. and six of the ¾ in. samples were not coated; these samples were set aside during the sample preparation process. For testing in the cone calorimeter three repeat tests were conducted for each incident flux level (35, 50, and 75 kW/m^2), each coating level (0, 3, 6, and 9), and each polyurethane finish (oil-based and water-based). Thus, 63 samples of nominal thickness ¼ in. plywood and 63 samples of nominal thickness ¾ in. plywood were prepared. A total of 144 samples (72 for each thickness) were required to fulfill the cone testing conditions. Table 3.3 provides a matrix of the tests conditions. Additional samples were prepared for the purpose of determining the minimum flux for ignition, surface temperatures, and back face temperatures for each thickness, each polyurethane finish, and each coating level.

Table 3.3 Matrix of Sample Specifications for Testing in the Cone Calorimeter

Plywood Thickness	Type of PU Finish	Number of Coatings	Heat Flux (kW/m^2)	Replicate Tests
¼ in. ¾ in.	Oil-based Water-based	0 3 6 9	35 50 75	3

Minwax® Polycrylic® Protective Water-Based Finish and Minwax® Fast-Drying Oil-Based Polyurethane were chosen because of their popularity and availability. Product information for each finish is provided in Appendix A. For simplicity, the two finishes are referred to as "water-based" and "oil-based" polyurethane throughout this paper. . Following the product directions, a two inch wide foam brush was used to apply the oil-based polyurethane while a two inch wide, high quality, synthetic brush was used to apply the water-based polyurethane. Although the types of brushes differed, the application method for each finish type was the same. Approximately one-quarter inch of the brush was dipped into the polyurethane. Firm, even strokes along the grain of the plywood were used to apply the finish to the sample. Care was taken to utilize the same application method to ensure equivalent coating from sample to sample.

After each coat the samples were allowed to dry for a minimum of twenty four hours. Once dry, the polyurethane layer was gently sanded with very fine sandpaper (220 grit) to ensure an even finish and proper adhesion of additional coats. The samples were then dusted and weighed to determine the net mass of polyurethane applied. Since the samples were stored under ambient laboratory conditions during the coating process, a set of 20 unfinished samples were used as control specimen to determine sample mass fluctuations due to changes in the ambient environment. The unfinished samples were weighed daily and the day to day mass variations were averaged to find a correction factor. Thus, a corrected sample mass was used to more accurately calculate the mass of polyurethane added. The need for this correction factor was most obvious on days where the humidity

changed significantly from the last mass reading. Without the correction factor, an erroneous negative coating mass would be recorded. Sample mass data are provided in Appendix B.

The application process was repeated until the desired coating level was achieved. During the coating process it was noted that the oil-based polyurethane was readily absorbed into the plywood. The water-based polyurethane formed a milky coating on the sample surface and required more time to dry. After several days of drying, the water-based polyurethane coated samples still felt tacky to the touch. If placed coating side down on a metal drying rack (after several days of drying), the water-based samples would gently stick to the rack. Also, the water-based polyurethane required at least six coats to be aesthetically pleasing to the discerning eye (2-3 coats are suggested by the manufacturer).

Samples with less than six coatings of water-based finish contained little bumps that were visually observed and could be felt along the surface. While 2-3 coats were suggested for the oil-based coating, best results were obtained with 3 or more coats. There was no visible difference between 3, 6, or 9 coats of oil-based polyurethane. Unlike the water-based polyurethane, the oil-based samples were smooth and did not feel tacky to the touch. There was a noticeable color difference between the two finishes after application and drying. The oil-based finish left the wood a richer, darker color while the water-based polyurethane allowed for the natural wood color to show through. The fumes from the oil-based finish were found to be stronger than those from the water-based finish. One would expect the cleanup for the water-based polyurethane to be easier than cleanup from the oil-

based polyurethane. However, since disposable foam brushes were used for the oil-based finish, cleanup after the oil-based coatings were applied was eliminated. More time and effort was required to clean out the brush used for the water-based polyurethane.

The mass of polyurethane applied increased approximately linearly with each additional coat, as shown in Figure 3.5. This suggests a consistent application method. The application rate was determined by dividing the total mass of polyurethane for each coating level per unit area by the number of coats. The application rates for both thicknesses and both coatings are shown in Figure 3.6.

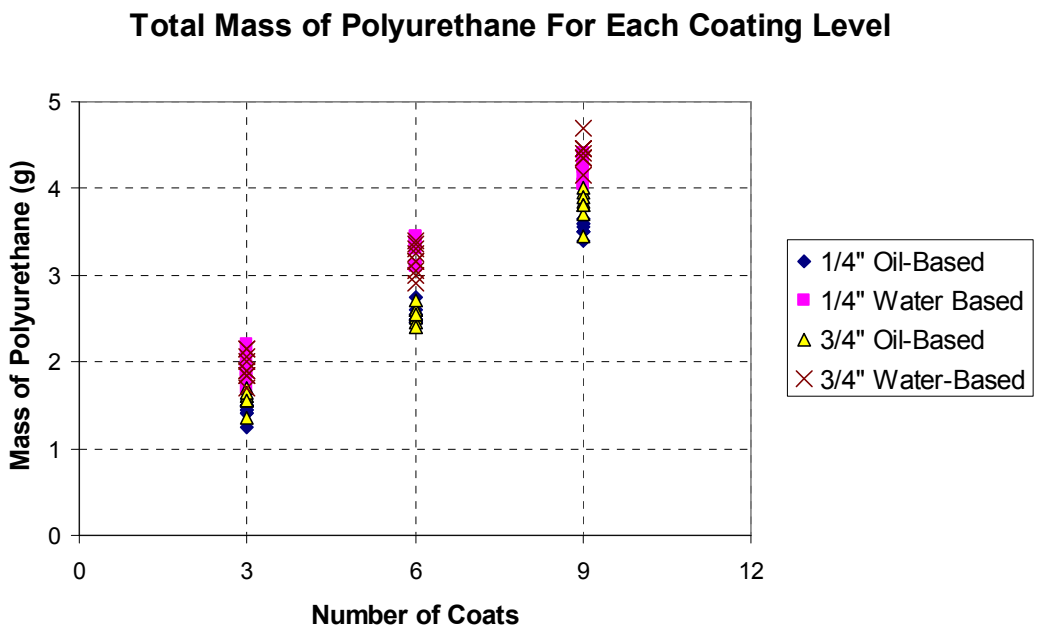

Figure 3.5 Total Mass of Polyurethane as a Function of Number of Coats

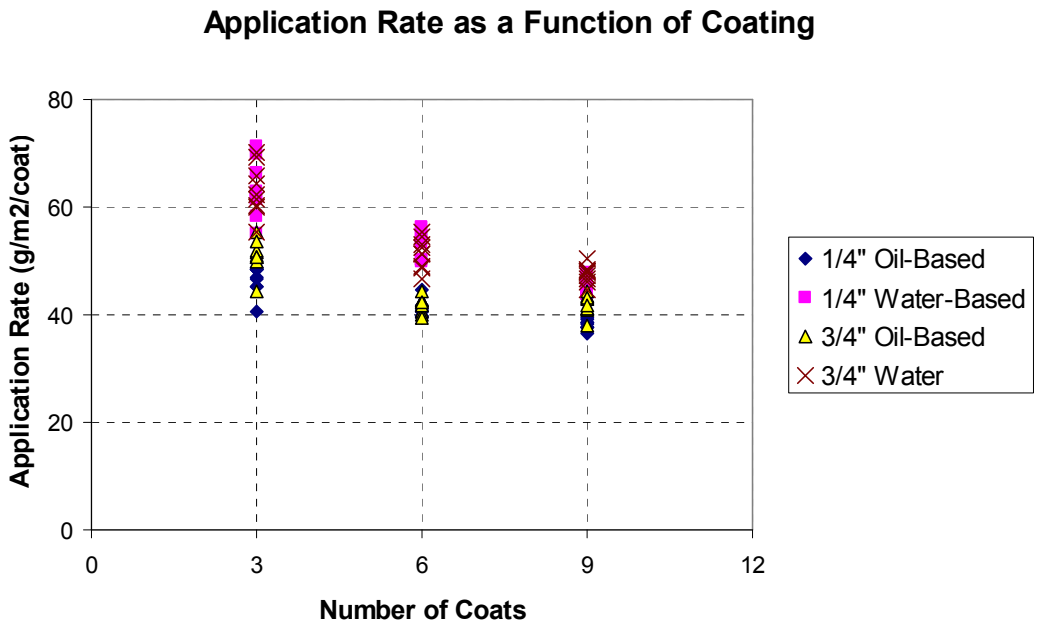

Figure 3.6 Application Rate by Coating Level

The sample thicknesses for all coating levels, including unfinished, were measured with a vernier caliper. The thickness of polyurethane applied was determined by subtracting the initial sample thickness from the sample thickness after application of polyurethane. Figures 3.7, 3.8, and 3.9 show the total sample thickness. Figure 3.10 shows the average thickness of polyurethane for each coating level. On average, more water-based polyurethane was applied than oil-based polyurethane for both the ¼ in. and ¾ in. samples. In general, the thickness of the polyurethane on the ¾ in. samples was greater than that on the ¼ in. samples.

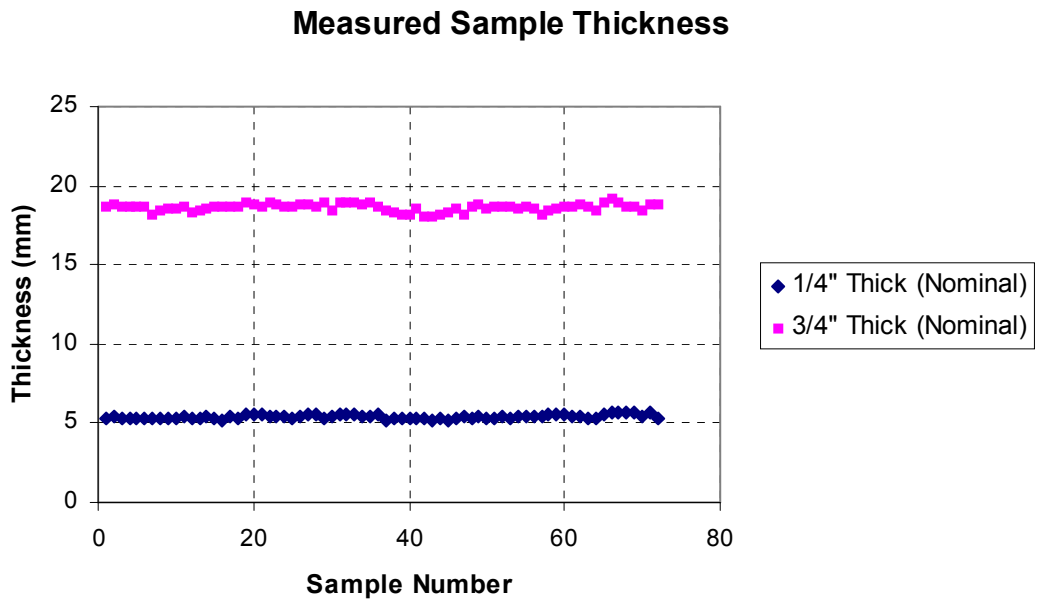

Figure 3.7 Measured Thickness of All Samples After Coating

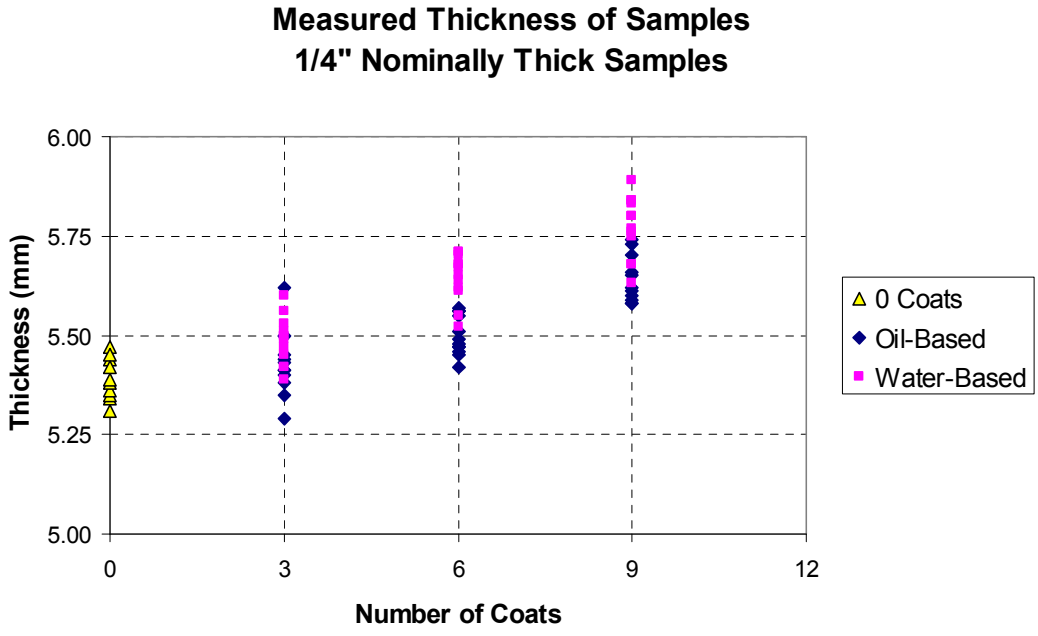

Figure 3.8 Measured Thickness of ¼ in. (Nominal) Thick Samples After Coating

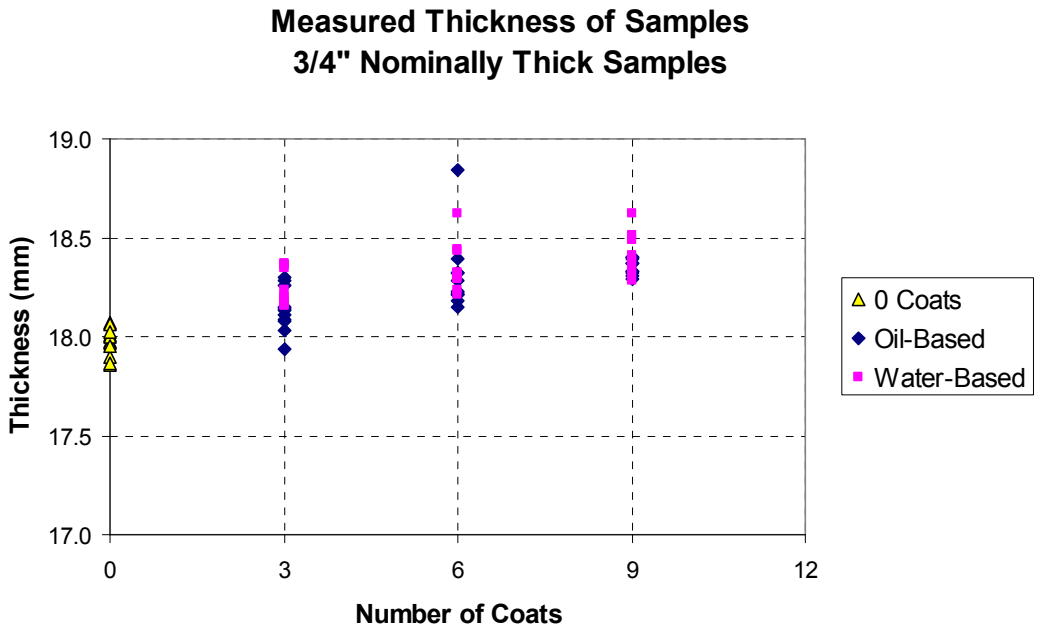

Figure 3.9 Measured Thickness of ¾ in. (Nominal) Thick Samples After Coating

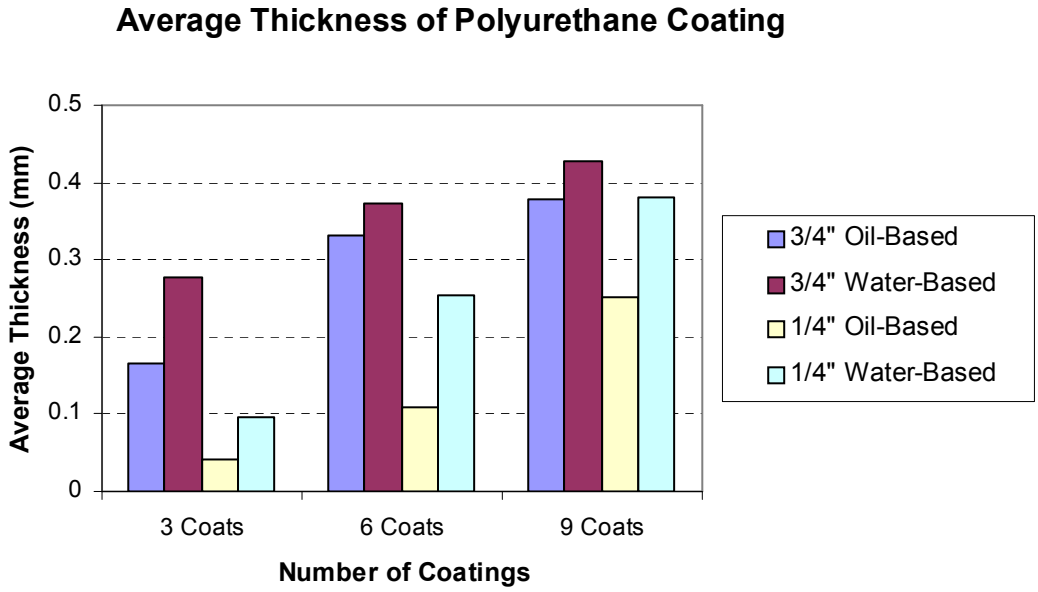

Figure 3.10 Average Thickness of Polyurethane For Each Coating Level

3.3 Sample Testing

Three types of test were performed for this project. The first set of tests utilized the cone calorimeter. The cone calorimeter used was produced by Fire Testing Technology (FTT) and is located at the Bureau of Alcohol Tobacco Firearms and Explosives Fire Research Laboratory in Ammendale, Maryland. The cone calorimeter and its data acquisition system allowed for relevant heat release data to be obtained. These data included the effective heat of combustion, heat release rate, mass loss rate, time to sustained flaming, smoke production rate and the nature of the gases produced during the combustion reaction. Not all of the available information was used for this project. However, all recorded data were retained for the possibility of future analysis. The second set of tests used the cone heater in the cone calorimeter to determine the critical flux for ignition. The last set of tests also used the cone heater, and thermocouples, to measure sample exposed surface and back face temperatures. All tests are described in more detail in the following three subsections.

3.3.1 Cone Testing

All tests were conducted in the horizontal position in general accordance with ASTM E1354-02a [2]. A steel retainer frame was used for all tests, causing the exposed surface area to be 88.36 cm^2. A study on the effects of retainer frame use found no significant differences in measured parameters in the cone calorimeter whether or not the retainer frame was used [22]. All samples were conditioned at 23ºC and 50% relative humidity for a minimum of one week prior to testing.

There were several observable differences in the burning behavior of the oil-based samples and the water-based samples. The flame from the water-based samples appeared to be "cloudier" than the flame from the oil-based samples. In general, the water-based samples flashed more before sustained ignition than the oil-based samples. While the oil-based and water-based coatings both started bubbling prior to ignition and several seconds after ignition, the bubbles of oil-based polyurethane were on average, larger than those of the water-based polyurethane. The bubbles on the oil-based sample measured approximately 2-5 mm in diameter, while the water-based polyurethane bubbles measured approximately 1-3 mm in diameter. After the oil-based finish stopped bubbling, it appeared to form a thin layer that started to crack and peel and then the sample started to show signs of "alligatoring." The bubbling for samples with 6 and 9 coats of oil-based polyurethane was more apparent that the samples with 3 coats. Also, the samples with 9 coats of oil-based finish generated bubbles that were more significantly raised (approximately 6 mm) above the surface than the water-based counterparts. On occasion, popping sounds were heard from the oil-based samples before and shortly after ignition. In general, the water-based coating behaved more like a liquid while the oil-based coating behaved more like an intumescent layer.

The ¼ in. thick samples bowed and curled anywhere from 2 to 4 minutes into testing, depending on the incident heat flux. Since the effects of a wire grid on the measure parameters was not known at the time of testing, one was not used to prevent the sample from bowing or curling. Bowing and curling was noticed in the ¾ in. samples as well but much further into the testing period; 10 to 20 minutes,

depending on the incident flux. All samples exhibited charring behavior and quick flame spread across the exposed surface upon ignition. Figure 3.11 shows the bowing (or curling) of a ¼ in. sample.

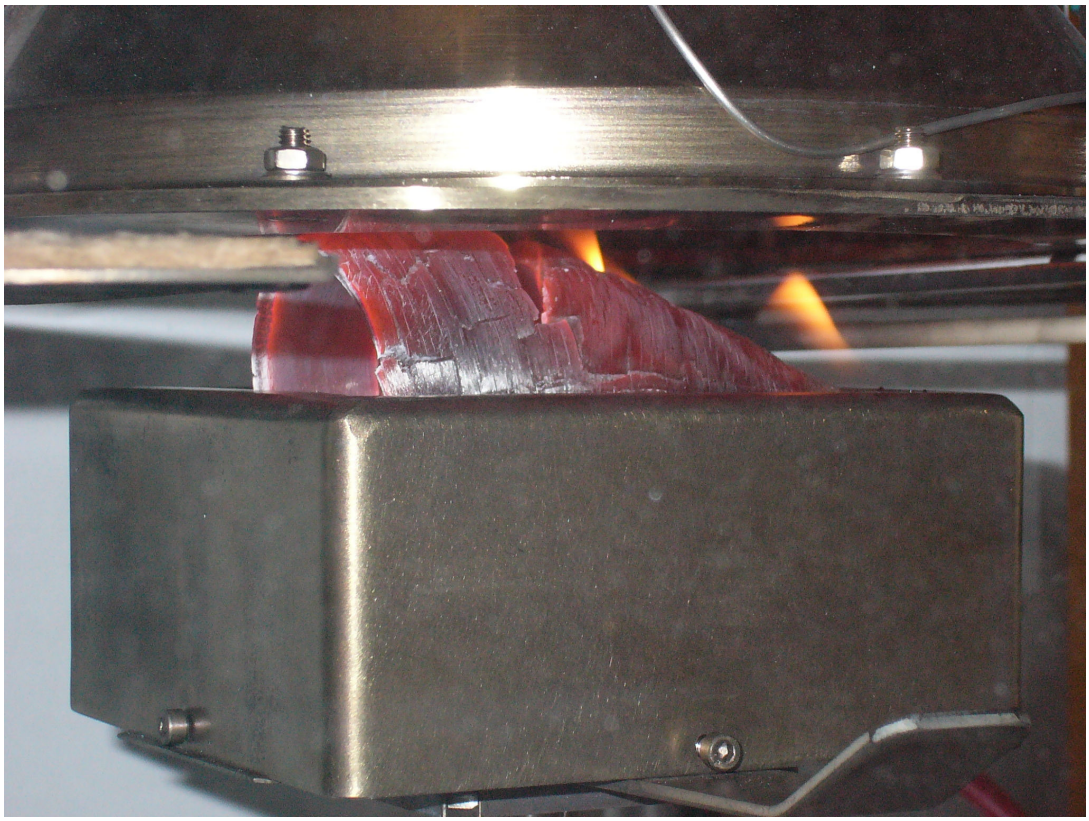

Figure 3.11 Bowing / Curling of ¼ in. Thick Sample

3.3.2 Minimum Flux for Ignition

The minimum flux for ignition is the lowest incident flux at which the sample ignites during a specified testing duration. The minimum flux for ignition differs from the critical flux for ignition. The minimum flux is the actual measured flux from experimentation, whereas the critical flux is the theoretical "minimum" based upon extrapolation to an indefinitely long ignition time [19]. The minimum flux for ignition was determined in general accordance to ASTM E1321 [13], but the exposure time was altered from 20 minutes to 30 minutes. Additional data were collected for a one-hour exposure time to be consistent with previous testing performed at ATF's Fire Research Laboratory. This data has been retained for further analysis. Finding the minimum flux for ignition was a trial and error process.

The samples were exposed to a constant incident heat flux (generated by the cone heater) for a period of thirty minutes. Depending on whether or not ignition occurred, the flux was adjusted and a replicate sample was tested. The minimum flux for ignition was found within 1 kW/m^2. That is, at a value 1 kW/m^2 below the reported minimum flux value, no ignition occurred within the 30-minute exposure time.

Table 3.4 Minimum Flux For Ignition Text Matrix

Plywood Thickness	Type of PU Finish	Number of Coatings	Heat Flux (kW/m^2)	Replicate Tests
¼ in. ¾ in.	Oil-based Water-based	0, 3, 6, 9	Varied (13 – 17)	None

3.3.3 Temperature at Ignition

During the ignition temperature tests, surface and back face temperatures were measured with 28-gauge, Type K thermocouples. The thermocouples were affixed to the sample with a staple placed at least 1.5 in. away from the thermocouple tip. With exception to the thermocouples, the samples were prepared in general accordance of ASTM E1354 [2]. The time to ignition was measured with a National Institute of Standards and Technology (NIST) calibrated stopwatch to $1/100^{th}$ of a second. Temperature data was recorded by the data acquisition system every second until flameout. Since the temperature data was only recorded every second, the temperature at ignition was estimated by interpolation of the recorded temperature data. For example, if the ignition time was 24.28 s, the temperature at ignition was estimated to be:

$$T_{ig} = 0.28(T_{25s} - T_{24s}) + T_{24s} \tag{3.2}$$

where T_{24s} is the temperature reading at 24 seconds and T_{25s} is the temperature reading at 25 seconds. Table 3.5 provides the test matrix for the ignition temperature tests.

Table 3.5 Surface and Back Face Temperature Text Matrix

Plywood Thickness	Type of PU Finish	Number of Coatings	Heat Flux (kW/m^2)	Replicate Tests
¼ in. ¾ in.	Oil-based Water-based	0, 3, 6, 9	35, 50, 75	None

Chapter 4. RESULTS AND DISCUSSION

4.1 Cone Calorimeter

The number of coats of polyurethane influences the ignition time. This is apparent in Figures 4.1, 4.2, and 4.3. In general, the ignition time decreases as the number of coats of polyurethane increases. The time to ignition for the oil-based samples was, in most cases, longer than the time to ignition for the water-based samples.

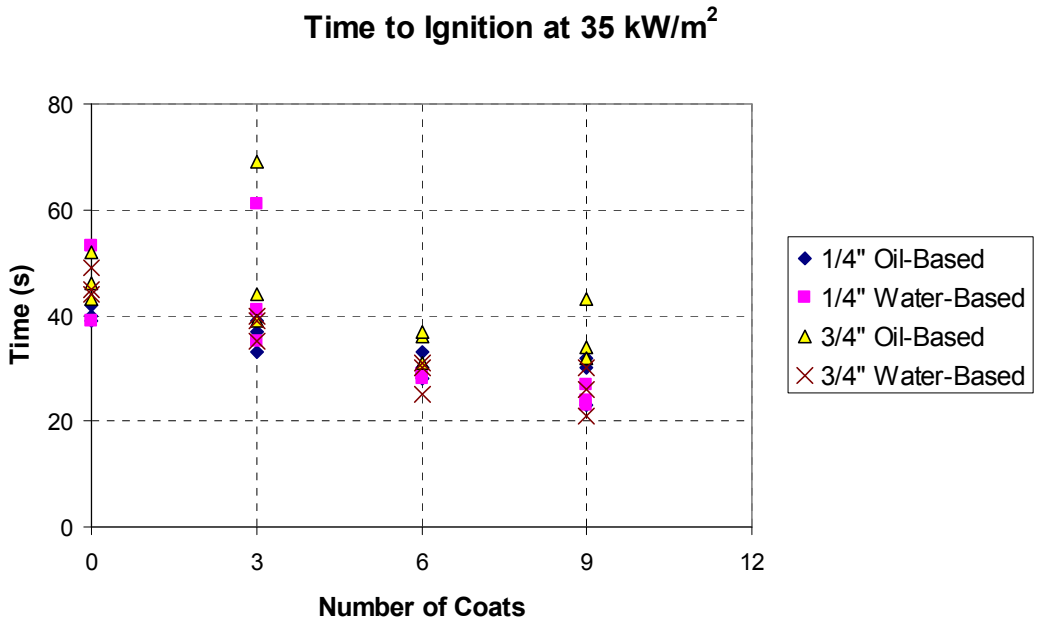

Figure 4.1 Ignition Time as a Function of Number of Coats at 35 kW/m^2

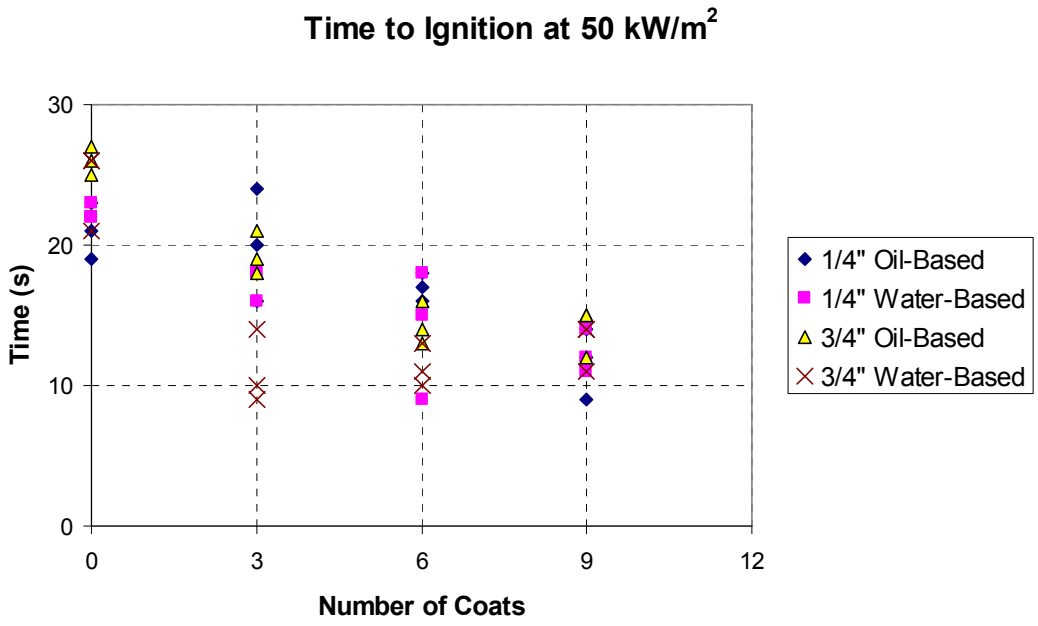

Figure 4.2 Ignition Time as a Function of Number of Coats at 50 kW/m^2

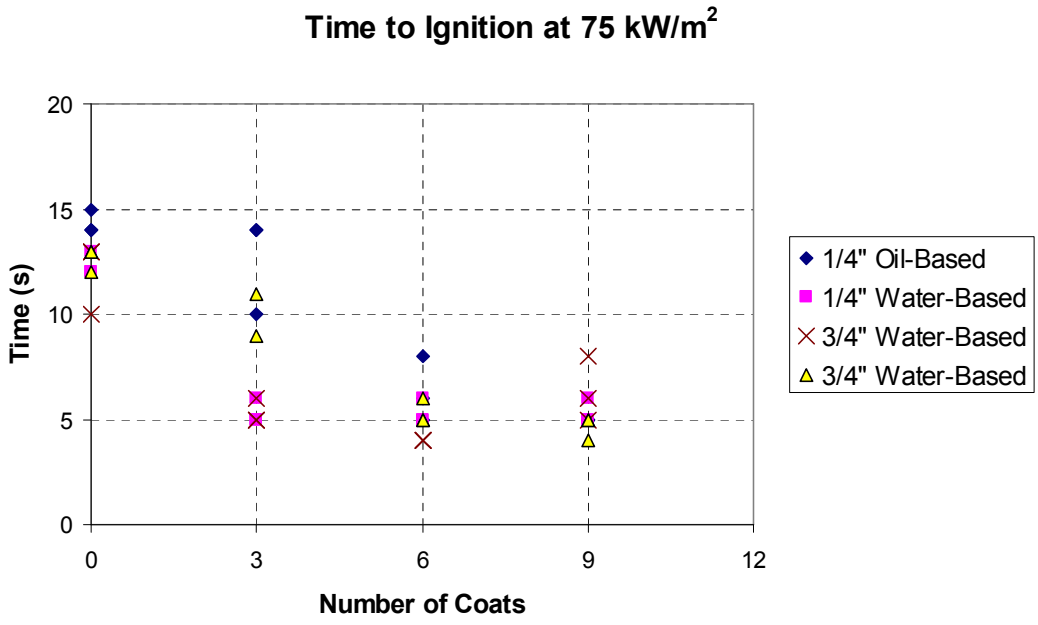

Figure 4.3 Ignition Time as a Function of Number of Coats at 75 kW/m^2

Figures 4.4, 4.5, and 4.6 provide another perspective of the ignition time data.

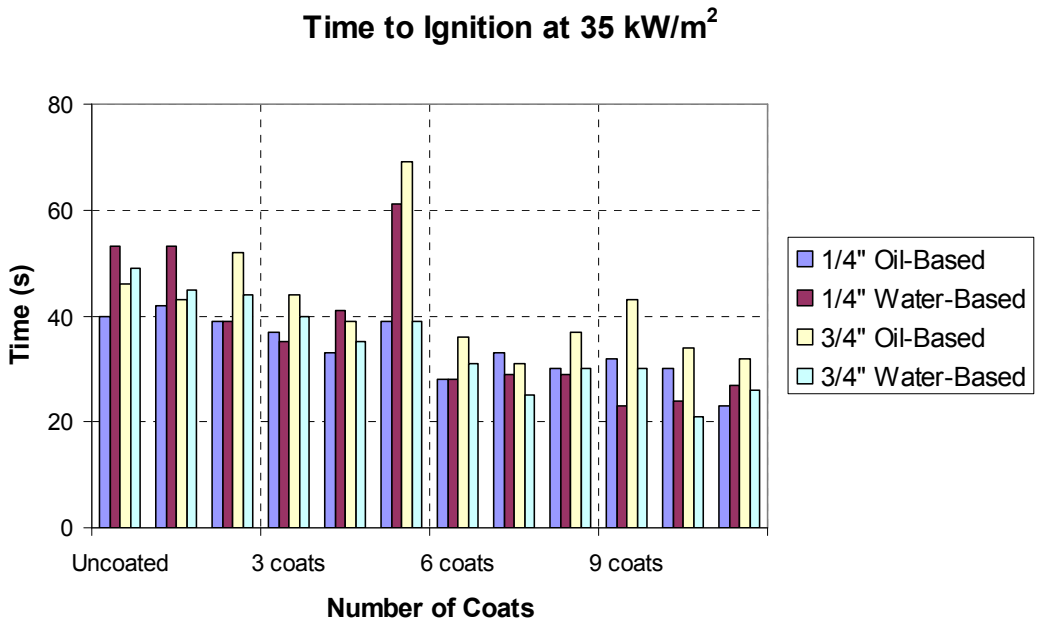

Figure 4.4 Ignition Time as a Function of Number of Coats at 35 kW/m^2

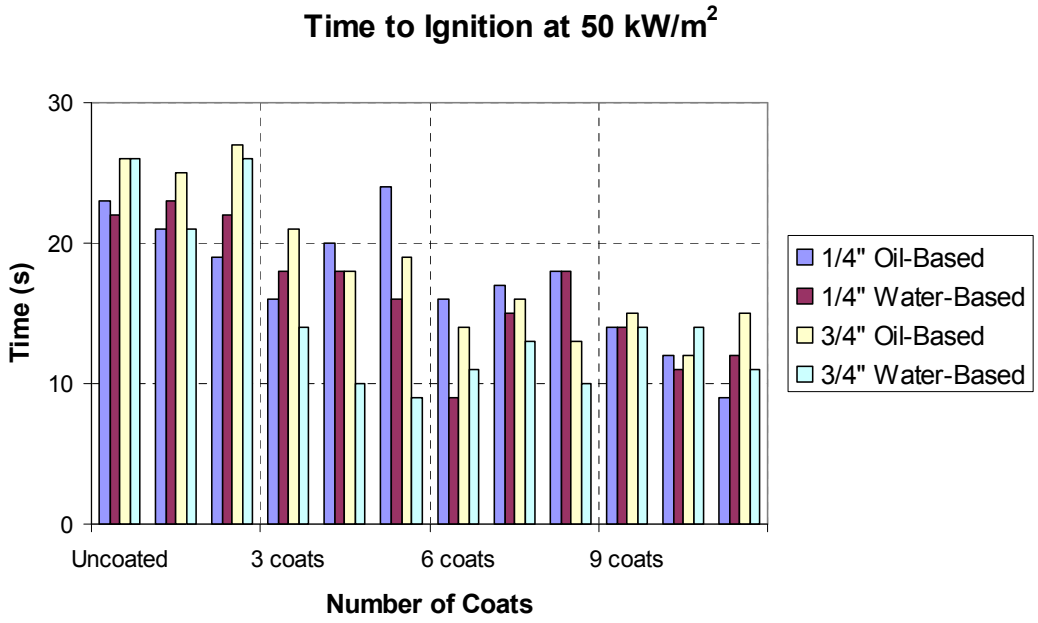

Figure 4.5 Ignition Time as a Function of Number of Coats at 50 kW/m2

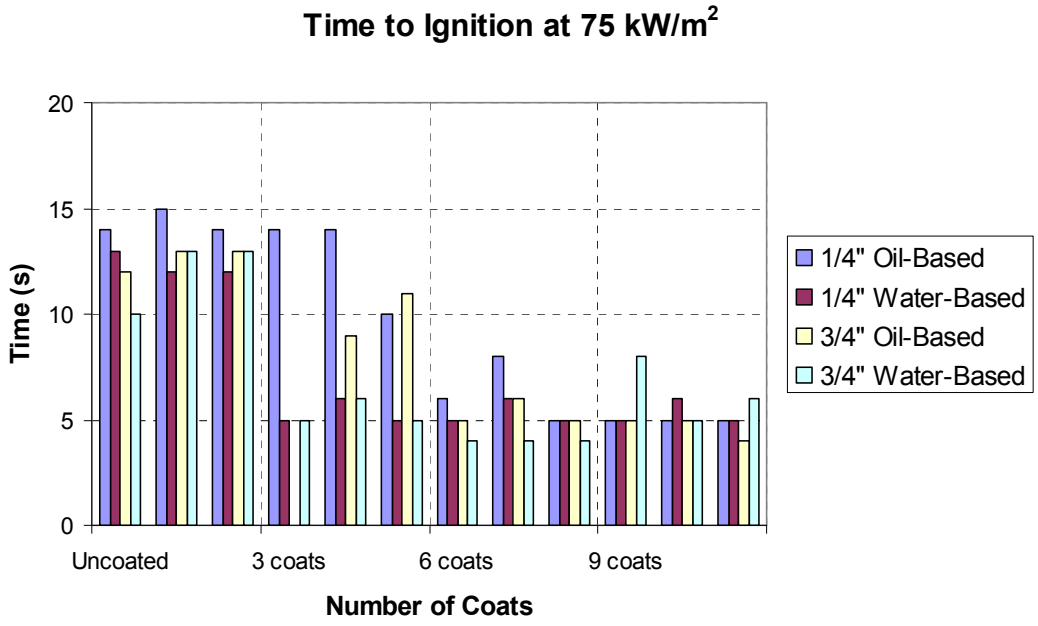

Figure 4.6 Ignition Time as a Function of Number of Coats at 75 kW/m^2

In order to provide a better sense of the effects coating has on the time to ignition, the ratio of the average ignition time for coating levels and coating types to the average ignition times for the uncoated samples was plotted as a function of the imposed heat flux. The times to ignition for the coated samples were as much as 2 to 3 times shorter than for the uncoated samples. The results of these comparisons are presented in Figures 4.7 and 4.8.

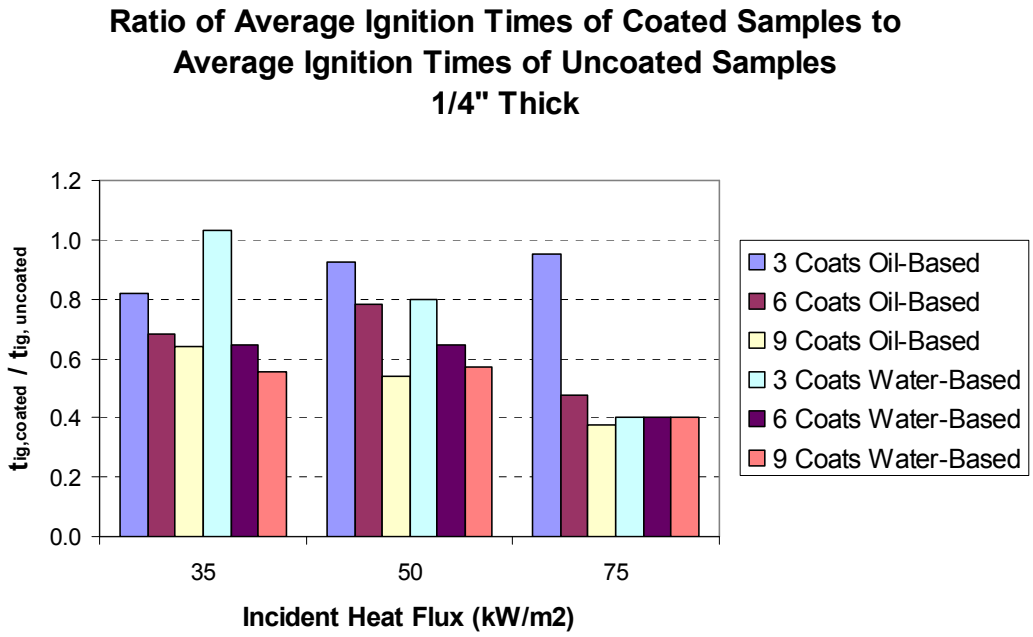

Figure 4.7 Ignition Time Ratios For ¼ in. Samples

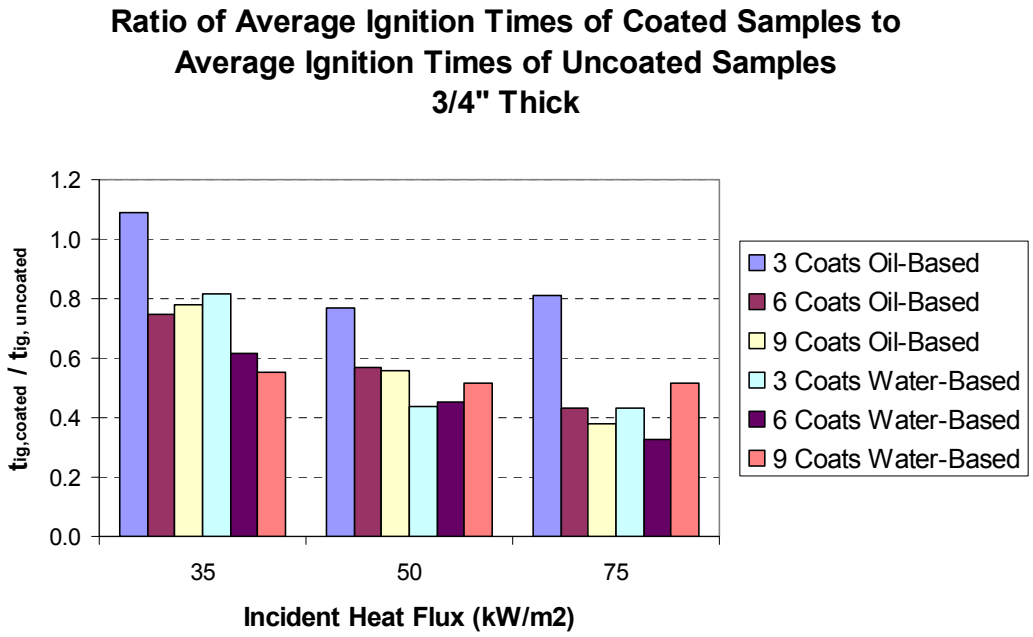

Figure 4.8 Ignition Time Ratios For ¾ in. Samples

The relationship between the time to ignition and the mass of polyurethane was also explored. For tests at 35 and 50 kW/m^2 (Figures 4.9 and 4.10) there appears to be a decrease in ignition time as the mass of polyurethane increases. However, for tests at 75 kW/m^2 (Figure 4.11), the ignition time seems to level off once the mass of polyurethane reaches approximately 2 grams.

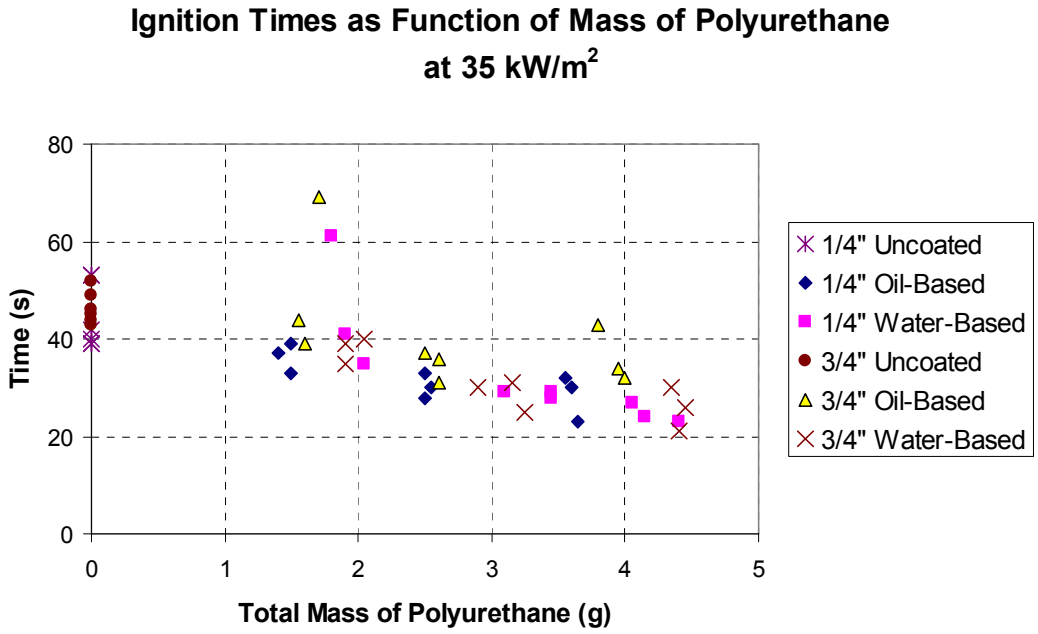

Figure 4.9 Ignition Time as a Function of Total Mass of Polyurethane at 35 kW/m^2

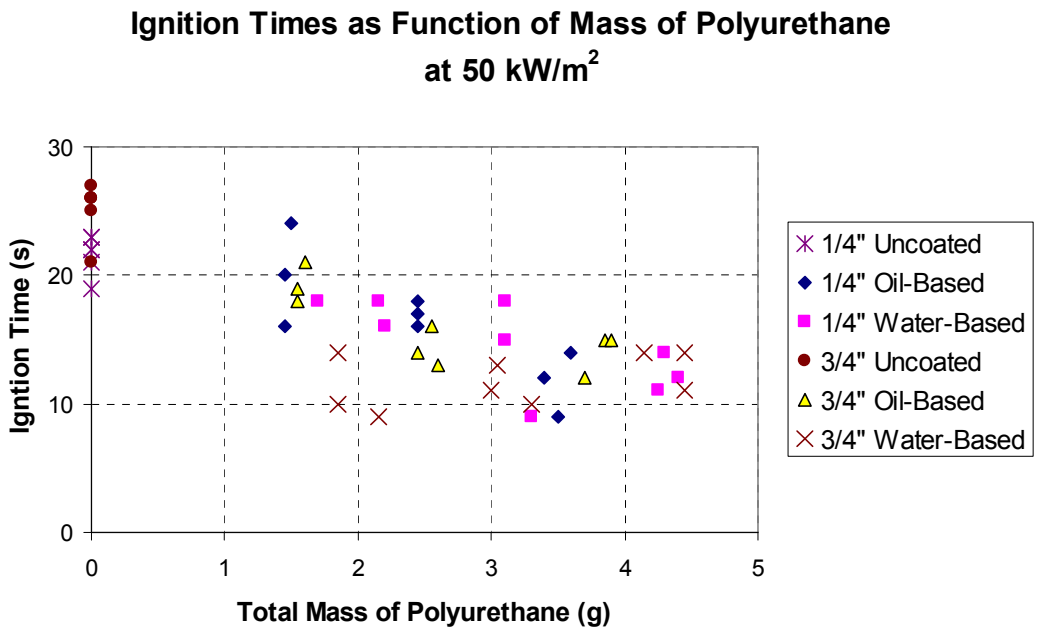

Figure 4.10 Ignition Time as a Function of Total Mass of Polyurethane at 50 kW/m^2

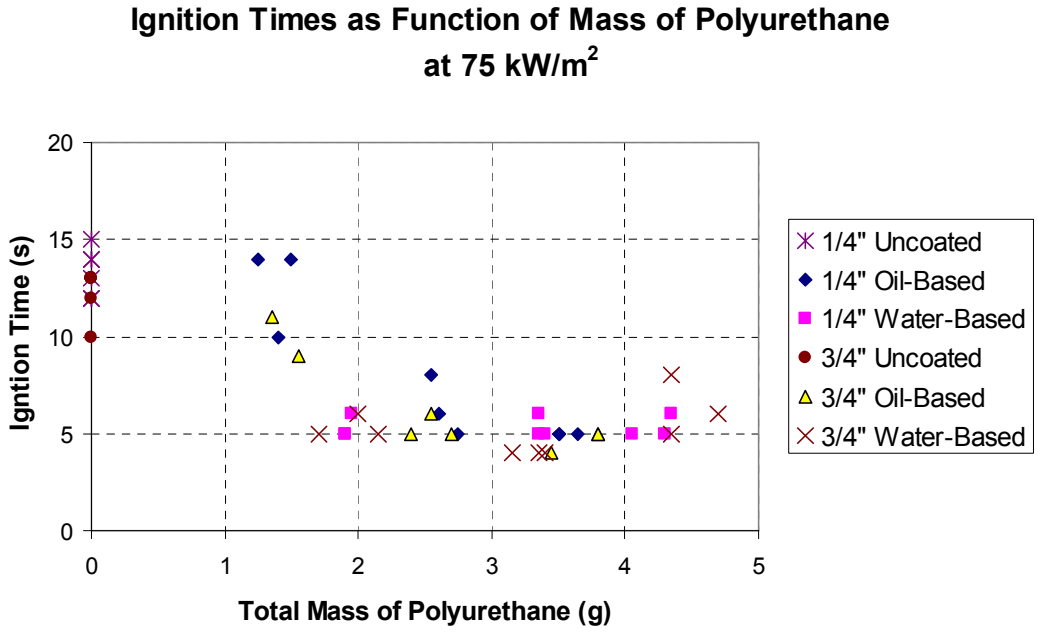

Figure 4.11 Ignition Time as a Function of Total Mass of Polyurethane at 75 kW/m^2

Figure 4.12 shows typical heat release per unit area (HRRPUA) and total heat released per unit area (THRPUA) curves. Typical mass loss curves are shown in Figure 4.13. The repeatability of the testing is illustrated in Figures 4.12 and 4.13.

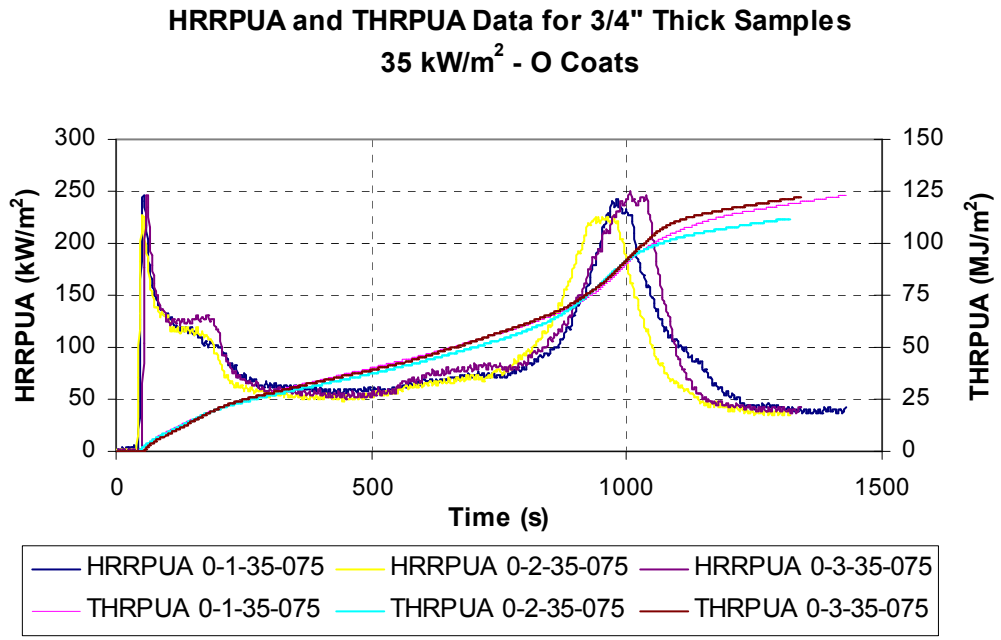

Figure 4.12 Heat Release Rate Per Unit Area and Total Heat Released Per Unit Area Curves: 3 Repeated Tests for ¾ in. Unfinished Samples

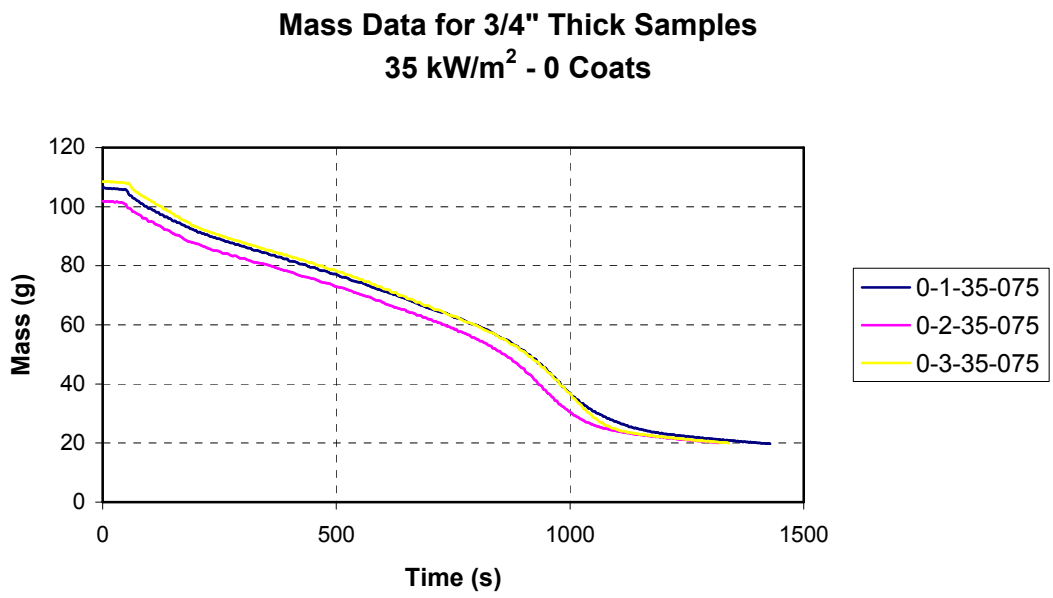

Figure 4.13 Typical Mass Loss Curves: 3 Repeated Tests for ¾ in. Unfinished Samples

The number of coats of polyurethane influences the measured peak heat release rates of the samples. The measured peak HRRPUA increases as the number of coats increases. Figure 4.14 displays the relationship between coatings and the measured peak HRRPUA for the ¼ in. samples as a function of the incident heat flux. Figure 4.15 displays the relationship between coatings and the measured peak HRRPUA for the ¾ in. samples as a function of the incident heat flux. The effects of coating levels on the measured peak heat release rate per unit area for each imposed flux are shown in Figures 4.16, 4.17, and 4.18.

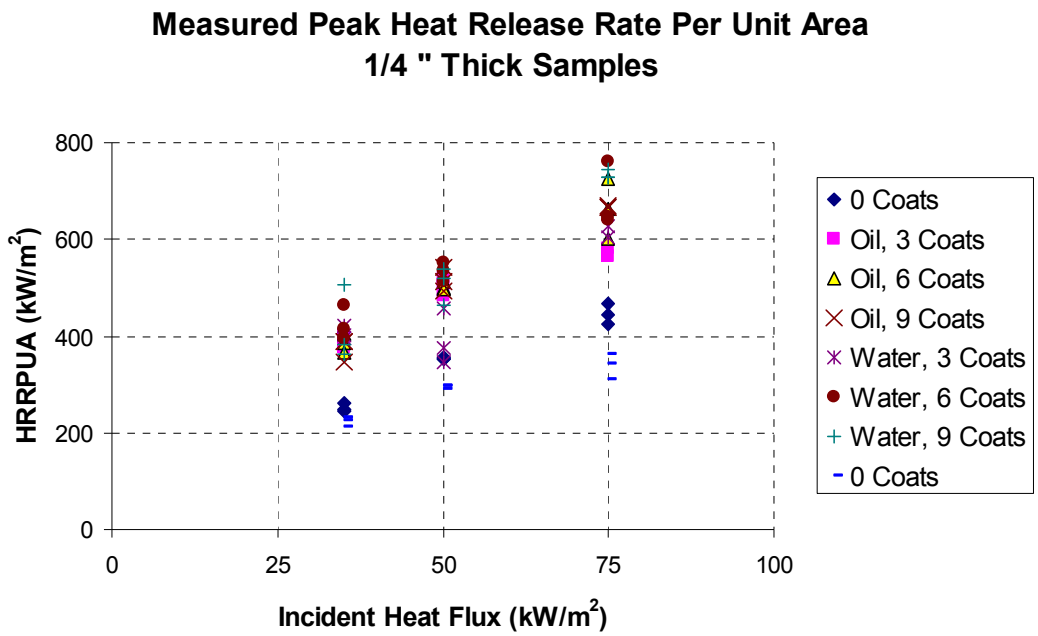

Figure 4.14 Effects of Coatings on the Peak HRRPUA For ¼ in. Samples

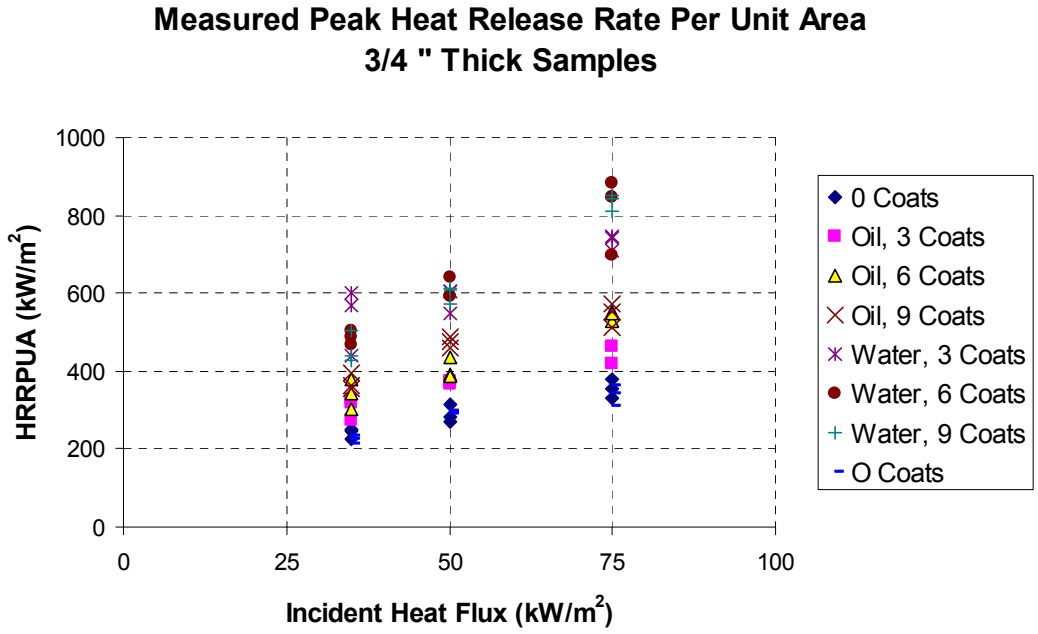

Figure 4.15 Effects of Coatings on the Peak HRRPUA For ¾ in. Samples

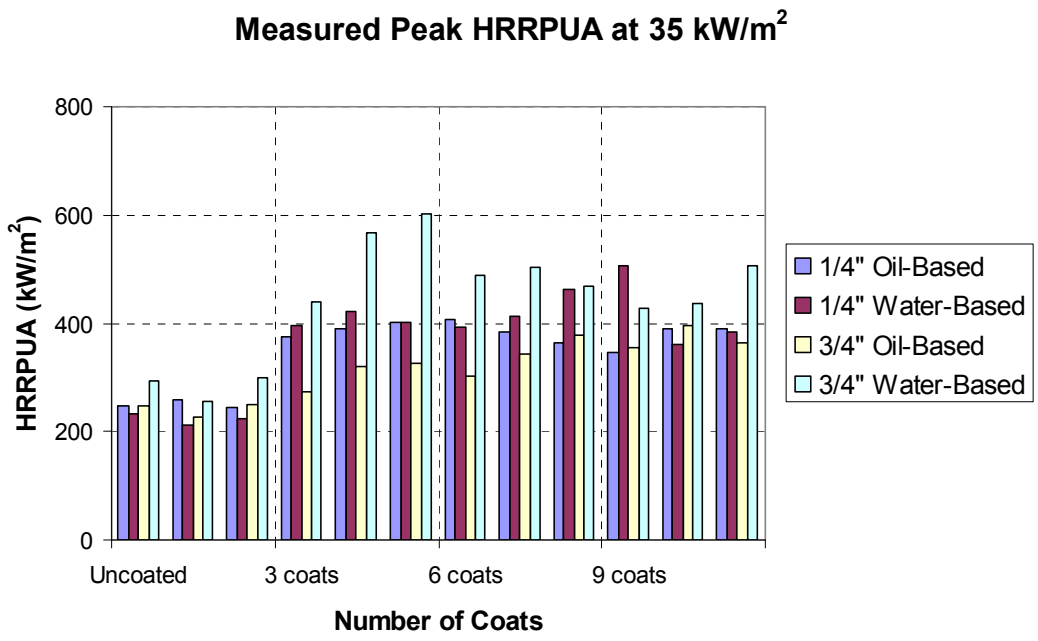

Figure 4.16 Effects of Coatings on the Measured Peak HRRPUA For an Imposed Flux of 35 kW/m^2

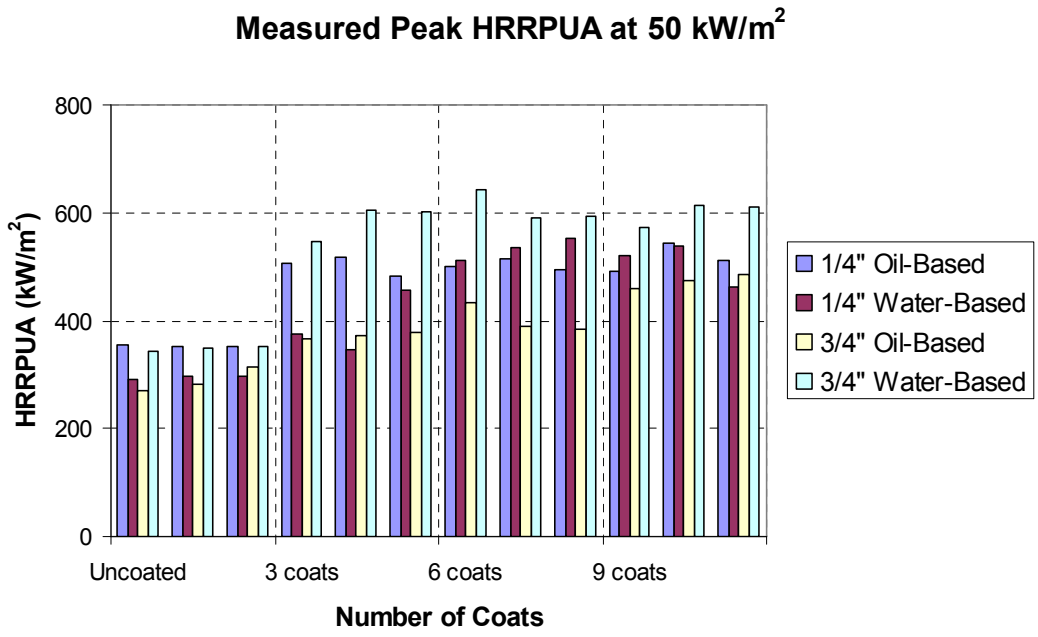

Figure 4.17 Effects of Coatings on the Measured Peak HRRPUA For an Imposed Flux of 50 kW/m^2

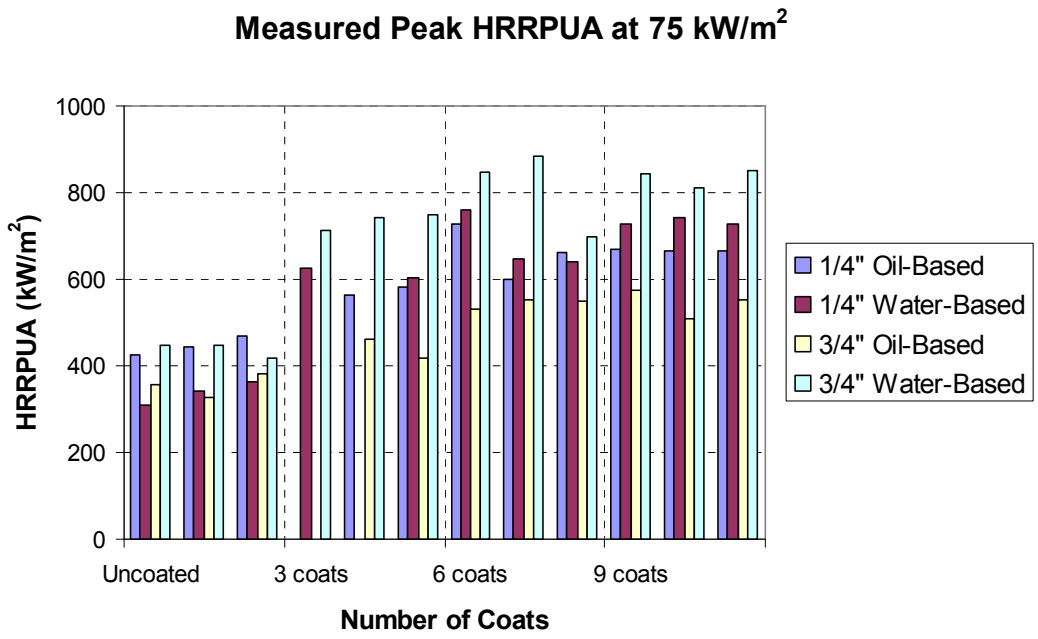

Figure 4.18 Effects of Coatings on the Measured Peak HRRPUA For an Imposed Flux of 75 kW/m^2

The number of finish coatings also influences the measured total heat released by the samples. The measured total heat released per unit area (THRPUA) increases slightly with the number of polyurethane coatings. Figure 4.19 displays the relationship between coatings and the measured THRPUA for the ¼ in. samples as a function of the incident heat flux. Figure 4.20 displays the relationship between coatings and the measured THRPUA for the ¾ in. samples as a function of the incident heat flux. The effects of coating levels on the measured total heat released per unit area for each imposed flux are shown in Figures 4.21, 4.22, and 4.23. As expected, the ¾ in. samples released significantly more total energy than the ¼ in. samples.

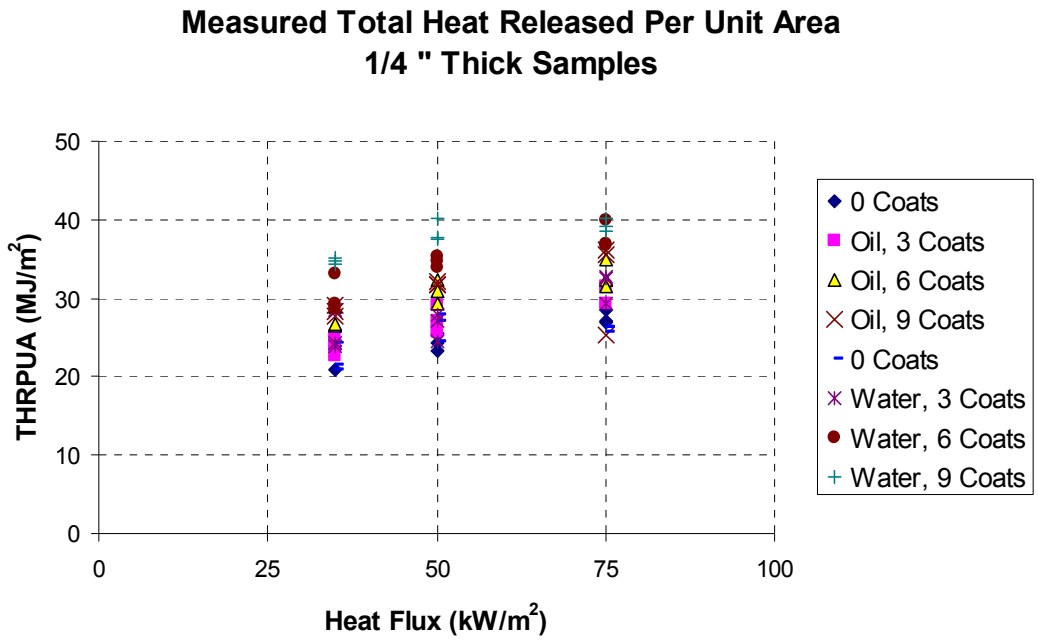

Figure 4.19 Effects of Coatings on the Total HRPUA For ¼ in. Samples

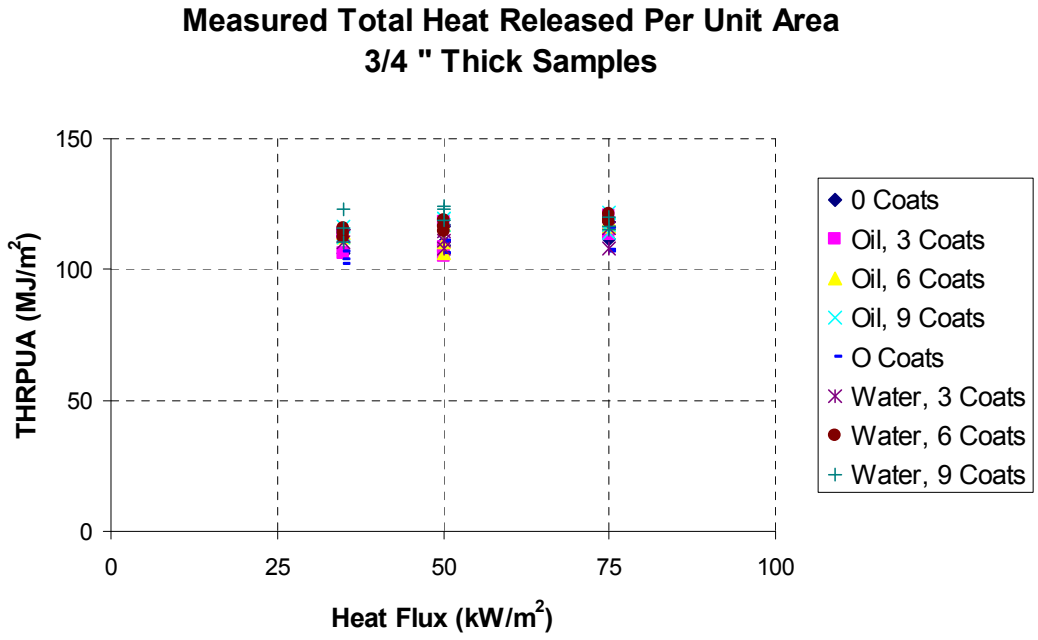

Figure 4.20 Effects of Coatings on the Total HRPUA For ¾ in. Samples

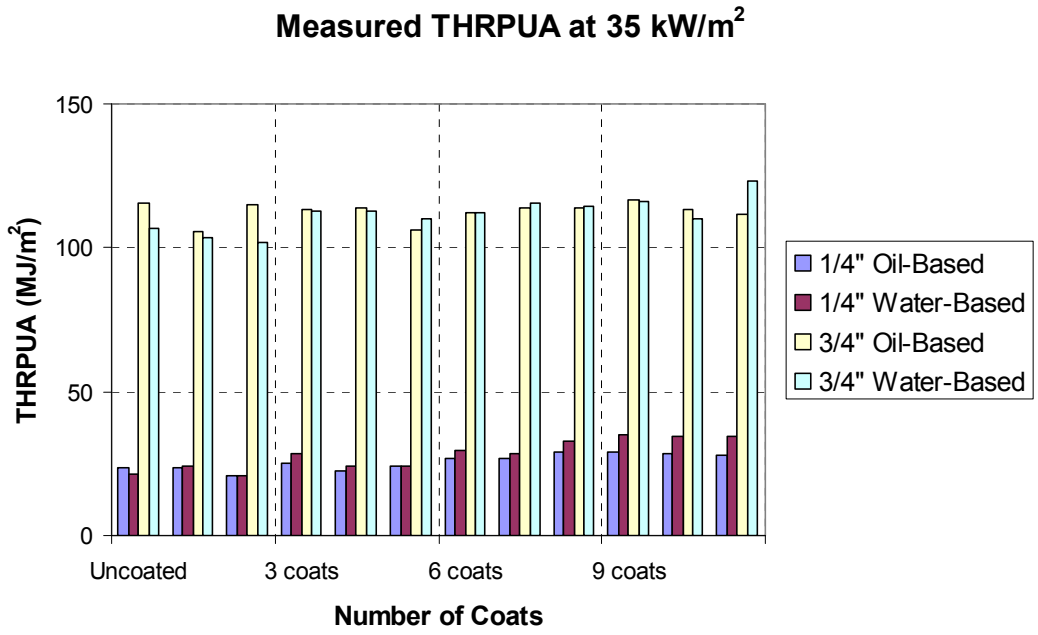

Figure 4.21 Effects of Coatings on the Measured THRPUA For an Imposed Flux of 35 kW/m^2

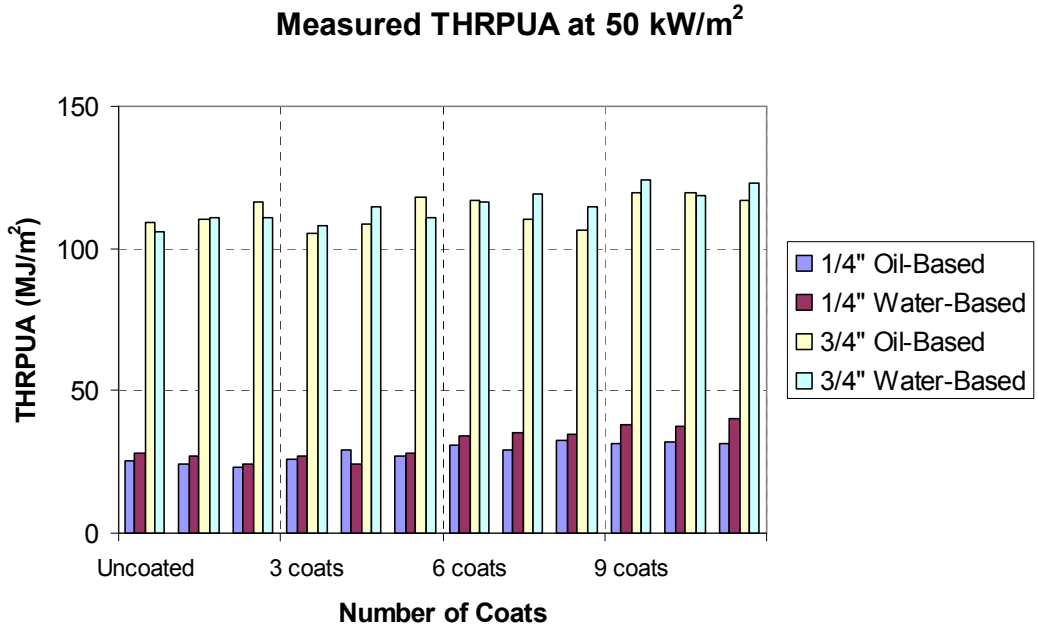

Figure 4.22 Effects of Coatings on the Measured Total HRPUA For an Imposed Flux of 50 kW/m^2

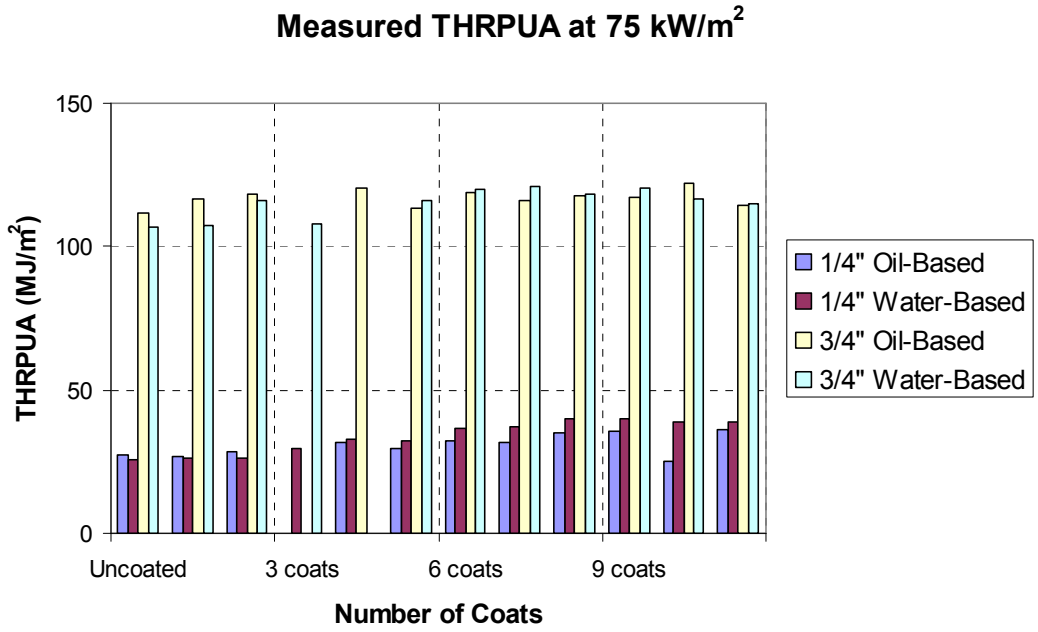

Figure 4.23 Effects of Coatings on the Measured Total HRPUA For an Imposed Flux of 75 kW/m^2

The number of finish coatings was found to influence the measured average effective heat of combustion of the samples. The average measured effective heat of combustion increased slightly with the number of polyurethane coatings. Figure 4.24 displays the relationship between coatings and the measured average effective heat of combustion. The same relationship is shown in Figure 4.25 with the range of the y-axis changed to "zoom" in on the effect coating has on the measured average effective heat of combustion.

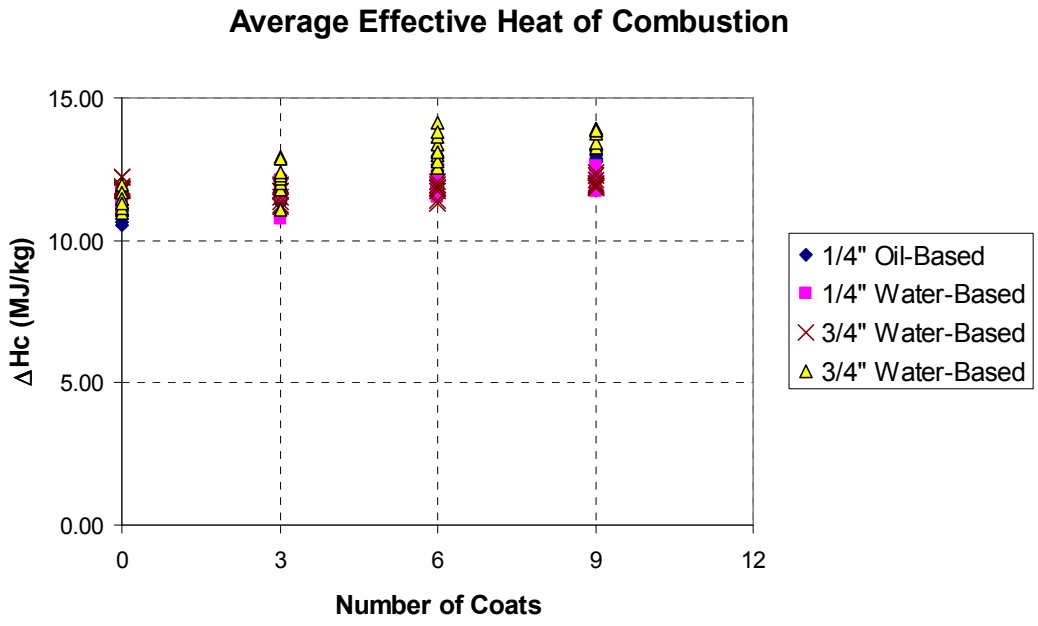

Figure 4.24 Effects of Coatings on the Measured Average Effective Heat of Combustion

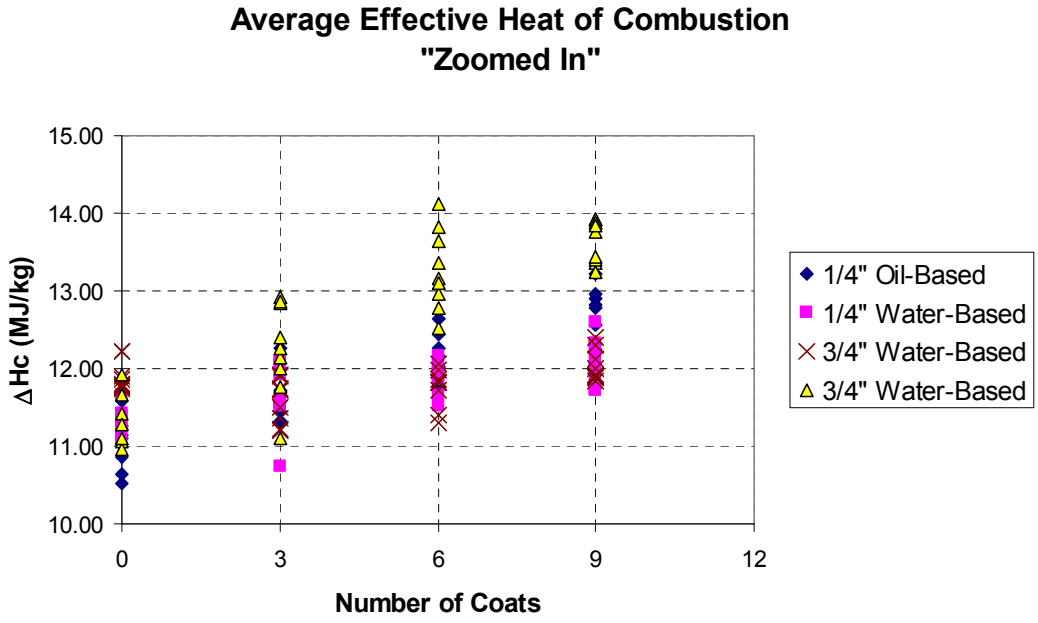

Figure 4.25 Effects of Coatings on the Measured Average Effective Heat of Combustion With Y-Axis Range Changed

The flammability parameter, b, was evaluated to determine whether or not the coatings increased the propensity for flame spread. The measured peak heat release rate per unit area, measured ignition time, and burning duration were plugged into Equation 2.8. The flame length parameter was assumed to be 0.01 m^2/kW and the burning duration was determined by the method described in Chapter 2.

As mentioned in Chapter 2, acceleratory flame spread is indicated if the value of the flammability parameter is positive, decay to extinction is expected if the flammability parameter is negative, and steady spread will theoretically occur if the flammability parameter is zero. Based on the data presented in Figures 4.26 and 4.27, flame spread would be expected for all coating thickness and heat flux scenarios. The flammability parameter is greater for the coated than the unfinished samples at all incident flux levels. With some exceptions, the flammability parameter reflects differences between the number and type of coating. The water-based coated samples tend to have a higher flammability parameter than the oil-based.

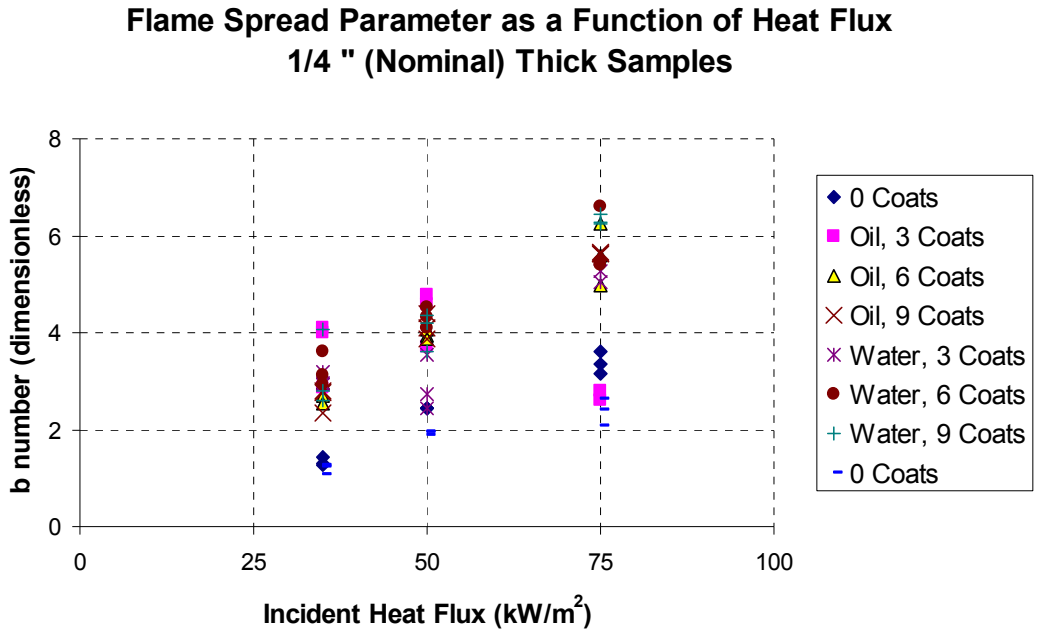

Figure 4.26 Flame Spread Parameter as a Function of the Imposed Flux Level For ¼ in. Samples

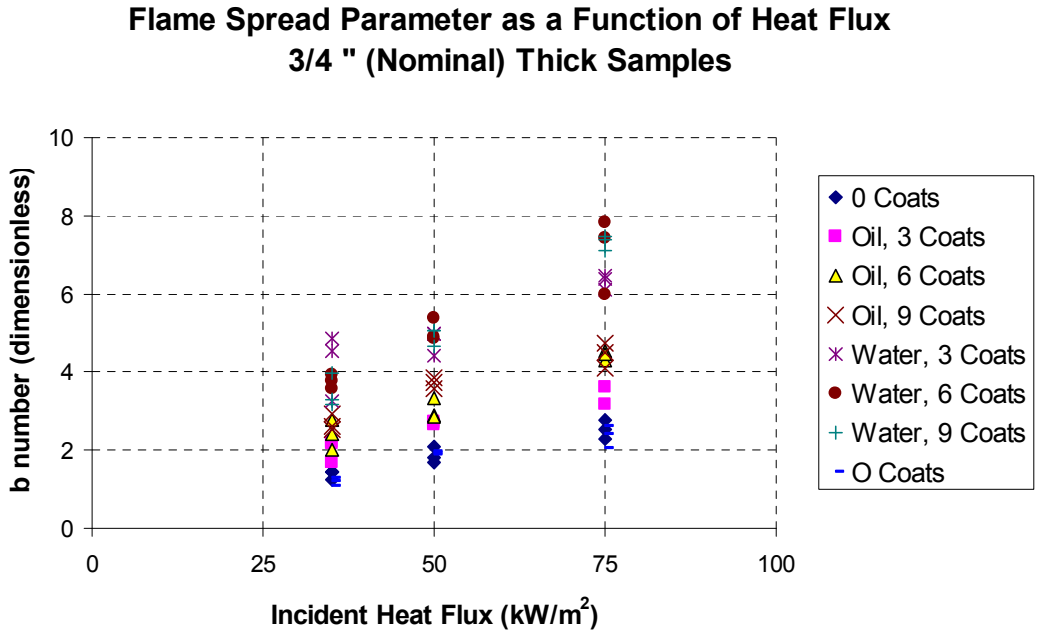

Figure 4.27 Flame Spread Parameter as a Function of the Imposed Flux Level For ¾ in. Samples

4.2 Minimum Heat Flux For Ignition

The minimum flux for ignition was found to be slightly dependent upon the thickness of the sample and on the number of coats and type of coating. In general, a lower minimum flux was found for the ¾ in. samples than for the ¼ in. samples and a lower flux for the water-based coated samples than the oil-based samples. Table 4.1 summarizes the minimum flux values measured and Figure 4.28 graphically displays the results.

Table 4.1 Minimum Heat Flux For Ignition

1/4" Samples		
# of Coats of PU	Type of PU	q_{ext} (kW/m^2)
0	---	14
3	Oil	16
6	Oil	16
9	Oil	15
3	Water	16
6	Water	15
9	Water	15

3/4" Samples		
# of Coats of PU	Type of PU	q_{ext} (kW/m^2)
0	---	15
3	Oil	14
6	Oil	14
9	Oil	14
3	Water	14
6	Water	14
9	Water	14

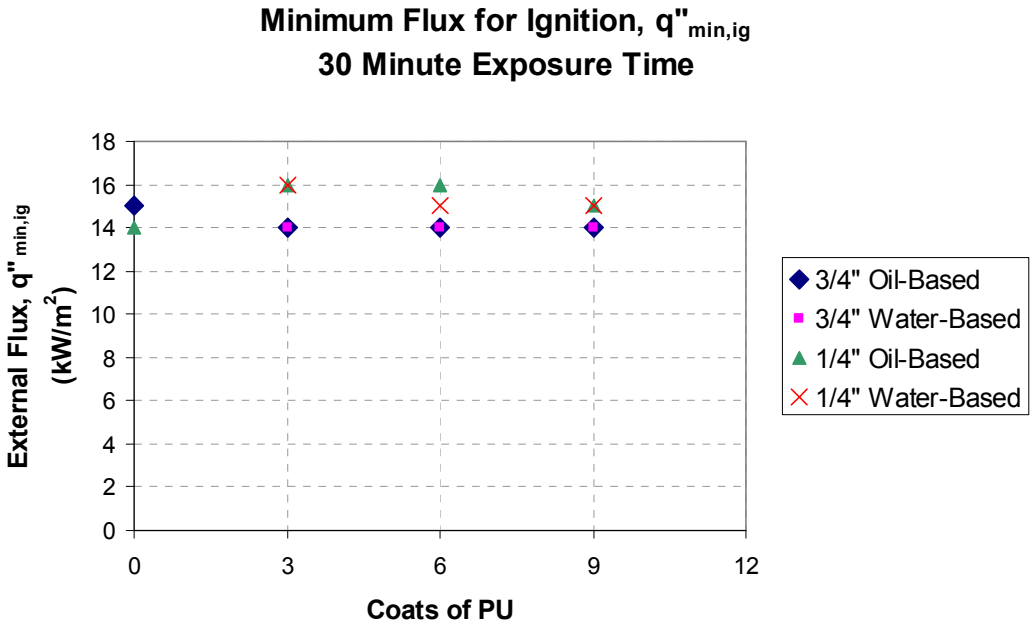

Figure 4.28 Minimum Flux For Ignition

4.3 Ignition Temperature

Measured ignition temperature data is provided in Appendix C. In general, it appears that the ignition temperature decreases with the number of coats for both oil-based and water-based polyurethane. The relationship between ignition temperature and number of coats of polyurethane is shown in Figures 4.34 and 4.35. Figure 4.29 shows measured surface and back face temperatures for an unfinished ¾ in. thick samples at an irradiance of 35 kW/m^2. Figures 4.30 and 4.31 show temperature data and general repeatability of temperature measurements.

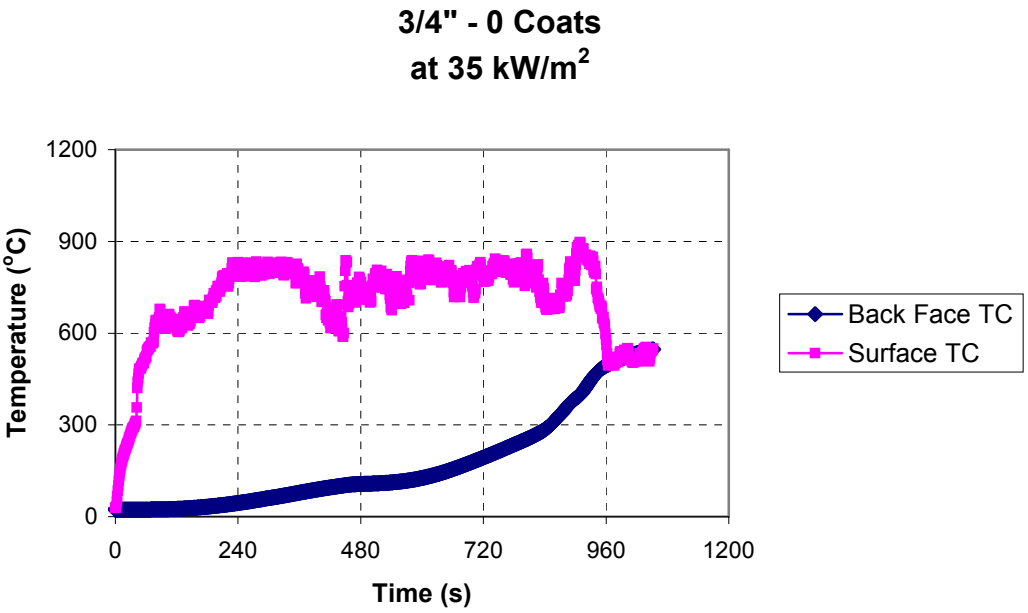

Figure 4.29 Measured Surface and Back Face Temperature Data for Unfinished Sample at Irradiance of 35 kW/m^2

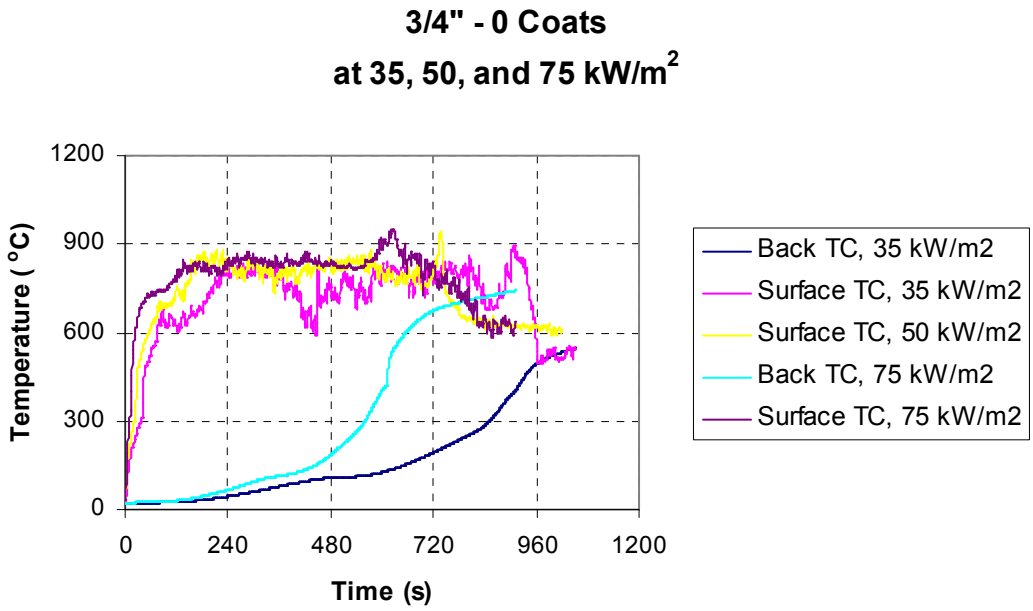

Figure 4.30 Measured Surface and Back Face Temperature Data for Unfinished Samples at 35, 50, and 75 kW/m^2

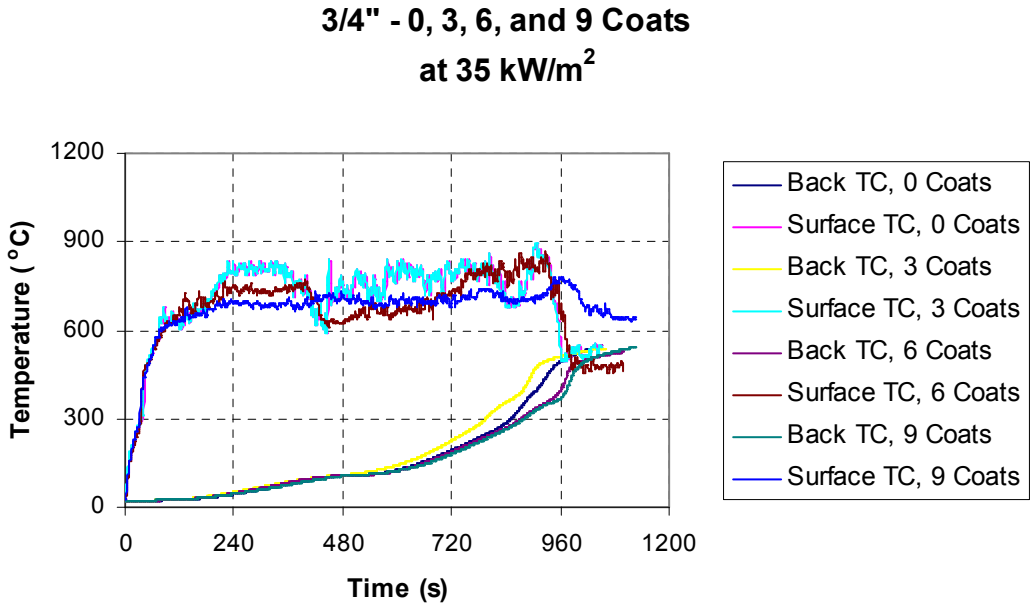

Figure 4.31 Measured Surface and Back Face Temperature Data for All Coating Levels at 35 kW/m^2 (Oil-Based Polyurethane)

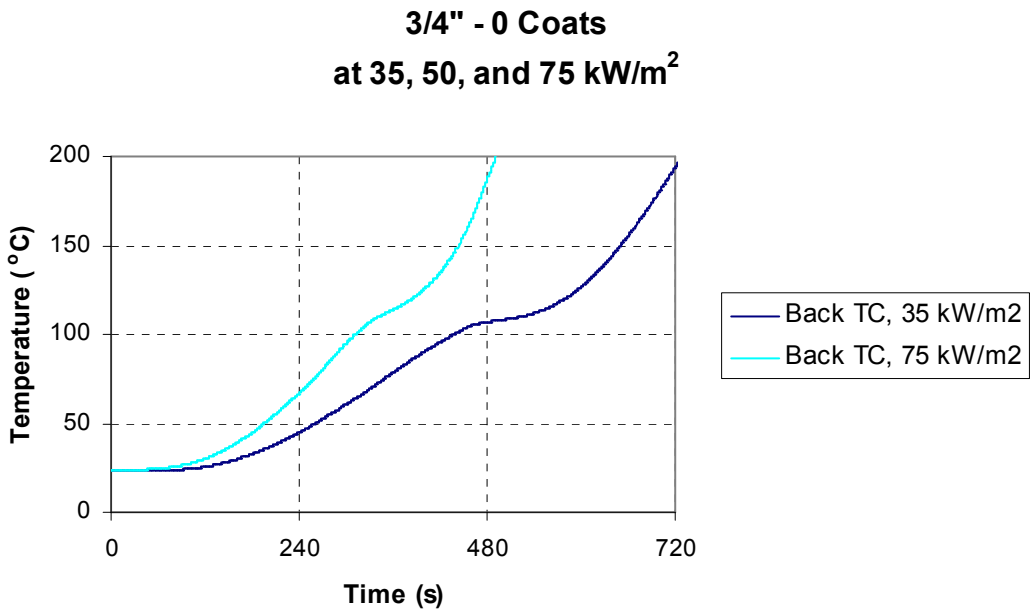

Figure 4.32 Measured Back Face Temperature Data for All Coating Levels at 35 kW/m^2

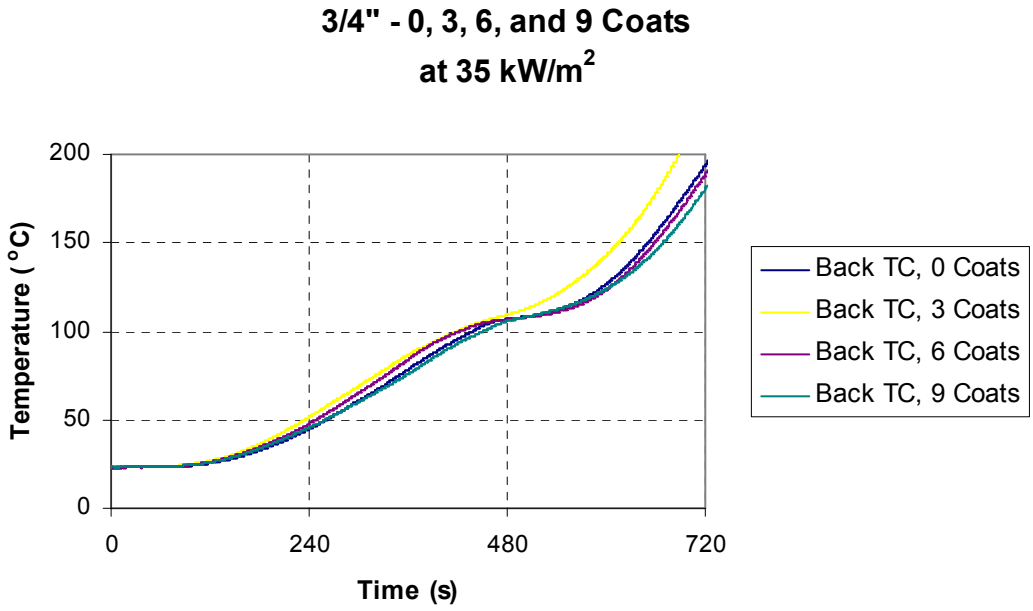

Figure 4.33 Measured Back Face Temperature Data for All Coating Levels at 35 kW/m2

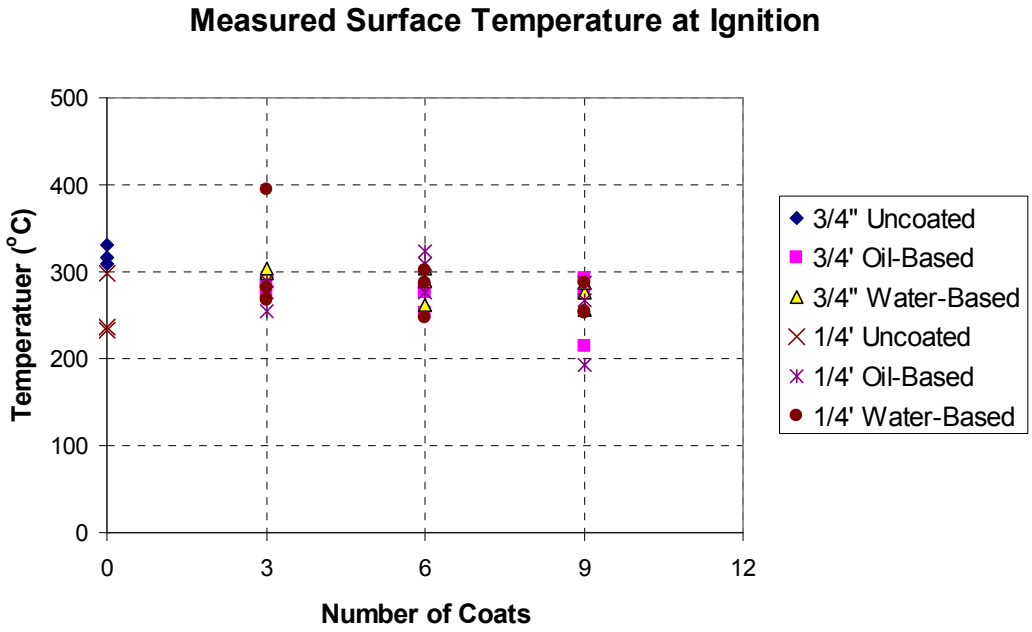

Figure 4.34 Measured Ignition Temperature as a Function of Number of Coats

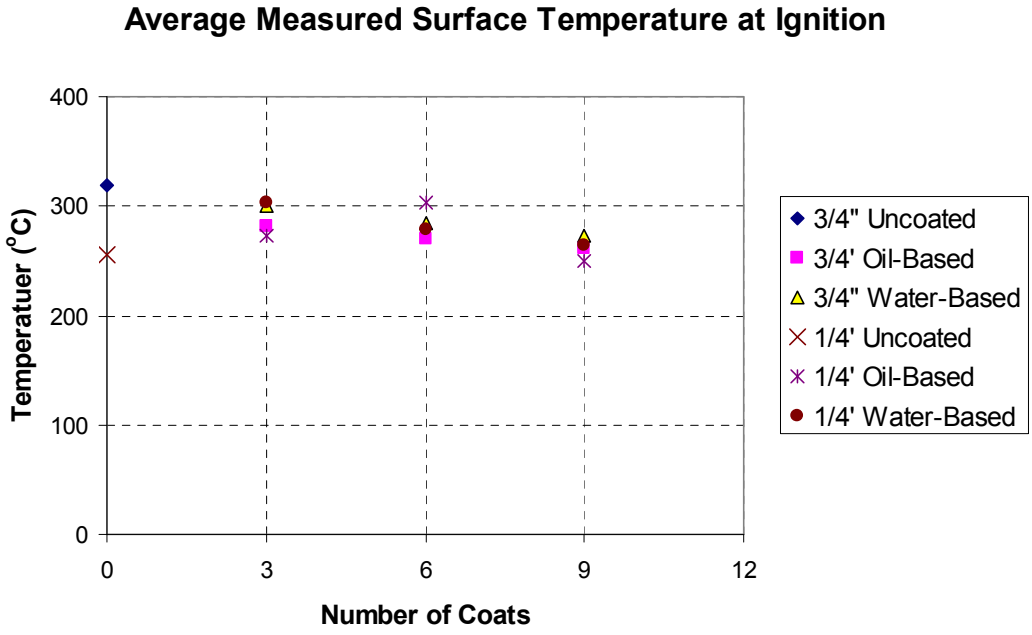

Figure 4.35 Average Measured Ignition Temperature as a Function of Number of Coats

The predicted ignition temperatures based on the measured minimum heat flux values were determined from solving Equation 2.5 by means of iteration. These calculations were based on an ambient temperature of 20 ºC, a constant convective heat transfer coefficient of 0.01 kW/m^2·K, and a surface with perfect emissivity ($\varepsilon = 1$). This method ignores conduction into the material and overestimates the actual ignition temperature by as much as 100 to 150 ºC.

The time to ignition was calculated two ways. The first is considered the "No Heat Loss" method and uses $\dot{q}''_{inc}$ as the denominator in Equation 2.6. The second method is referred to as the "Tewarson" method and utilizes Equation 2.6 as it is found in Chapter 2. A comparison between the predicted and measured ignition time averages, shows better agreement between the measured ignition times and those determined with $\dot{q}''_{net}$ as the denominator. How close the predicted values are to the measured averages is dependent on the number of coats of polyurethane. The predicted ignition times using the No Heat Loss method are, for the most part, factors of 2 to 3 higher than the measured values for the given incident heat flux. The ignition times predicted by the Tewarson method are closer to the actual measured values for the uncoated and 3 coats of oil-based polyurethane samples at the 35 and 50 kW/m^2 heat flux. While the predicted ignition time for 75 kW/m^2 is closer to the ignition times for samples with 6 or more coats of polyurethane. The ignition times predicted the Tewarson method are, at most, either 2 times as high or 2 times lower than the average measured values.

Table 4.2 Predicted Temperature and Time to Ignition Values

			No Heat Loss $\dot{q}''_{inc}$			Tewarson $\dot{q}''_{net}$		
		q =	35 (kW/m^2)	50 (kW/m^2)	75 (kW/m^2)	35 (kW/m^2)	50 (kW/m^2)	75 (kW/m^2)
$q''_{min,ig}$ (kW/m^2)	T_{ig} (^{o}C)	T_{ig} (K)	t_{ig} (s)	t_{ig} (s)	t_{ig} (s)	t_{ig} (s)	t_{ig} (s)	t_{ig} (s)
14	387	660	18.57	9.10	4.04	56.82	18.56	6.30
15	400	673	19.90	9.75	4.33	60.89	19.89	6.75
16	412	685	21.20	10.38	4.61	64.87	21.18	7.19

Table 4.3 Average Measured Time to Ignition Values

		q =	35 kW/m^2	50 kW/m^2	75 kW/m^2
Thickness in.	Coats PU	PU Type	Avg. t_{ig} (s)	Avg. t_{ig} (s)	Avg. t_{ig} (s)
1/4	0	n/a	44	22	13
1/4	3	oil	36	20	13
1/4	6	oil	30	17	6
1/4	9	oil	28	12	5
1/4	3	water	46	17	5
1/4	6	water	29	14	5
1/4	9	water	25	12	5
3/4	0	n/a	47	25	12
3/4	3	oil	51	19	10
3/4	6	oil	35	14	5
3/4	9	oil	36	14	5
3/4	3	water	38	11	5
3/4	6	water	29	11	4
3/4	9	water	26	13	6

The theoretical thermal inertia was found to be 0.215 $(kW/m^2 \cdot K)^2 \cdot s$ from the reported material properties for oak provided in Table 3.1. Calculated thermal inertias were determined by evaluating Equation 2.7 with the "No Heat Loss" method ($\dot{q}''_{inc}$ in the numerator) and the "Tewarson" method ($\dot{q}''_{net} = \dot{q}''_{inc} - \dot{q}''_{\min}$ in the numerator). The calculations were based on measured ignition times, measured ignition temperature values, and either the incident heat flux or the net heat flux. The effective thermal inertias determined using the "No Heat Loss" method ranged from a minimum of 0.41 to a maximum of 2.11 $(kW/m^2 \cdot K)^2 \cdot s$. The No Heat Loss method resulted in effective thermal inertias that are approximately 2 to 10 times higher than the reported values for oak. Figures 4.36 and 4.37 show the effective thermal inertia as function of the incident heat flux for all coating levels and thicknesses using the No Heat Loss method. The effective thermal inertias determined using the "Tewarson" method ranged from a minimum of 0.19 to a maximum of 1.10 $(kW/m^2 \cdot K)^2 \cdot s$. The Tewarson method produced effective thermal inertias that correlate better to the reported effective thermal inertia. However, the predicted thermal inertias using the Tewarson method were as much as 5 times the reported value. Figures 4.38 and 4.39 show the effective thermal inertias as a function of the incident heat flux for all coating levels and thicknesses using the Tewarson method. In general the coated samples have a lower effective thermal inertia than the unfinished plywood.

Table 4.4 Effective Thermal Inertias Based on Measured Averages of T_{ig} and t_{ig}

			No Heat Loss $\dot{q}''_{inc}$			Tewarson $\dot{q}''_{net}$		
		q =	35 kW/m^2	50 kW/m^2	75 kW/m^2	35 kW/m^2	50 kW/m^2	75 kW/m^2
Thickness in.	Coats PU	PU Type	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s	$(k\rho c)_{eff}$ (kW/m^{2}K)^{2}s
1/4	0	n/a	1.25	1.24	1.72	0.41	0.61	1.10
1/4	3	oil	0.88	0.99	1.41	0.29	0.49	0.90
1/4	6	oil	0.59	0.68	0.57	0.19	0.33	0.36
1/4	9	oil	0.84	0.71	0.68	0.28	0.35	0.44
1/4	3	water	0.89	0.69	0.48	0.29	0.34	0.30
1/4	6	water	0.67	0.67	0.57	0.22	0.33	0.37
1/4	9	water	0.64	0.66	0.64	0.21	0.32	0.41
3/4	0	n/a	0.81	0.90	0.99	0.27	0.44	0.63
3/4	3	oil	1.16	0.90	1.05	0.38	0.44	0.67
3/4	6	oil	0.87	0.73	0.61	0.29	0.36	0.39
3/4	9	oil	0.98	0.77	0.58	0.32	0.38	0.37
3/4	3	water	0.75	0.44	0.48	0.25	0.22	0.31
3/4	6	water	0.64	0.51	0.41	0.21	0.25	0.26
3/4	9	water	0.62	0.64	0.71	0.21	0.32	0.45

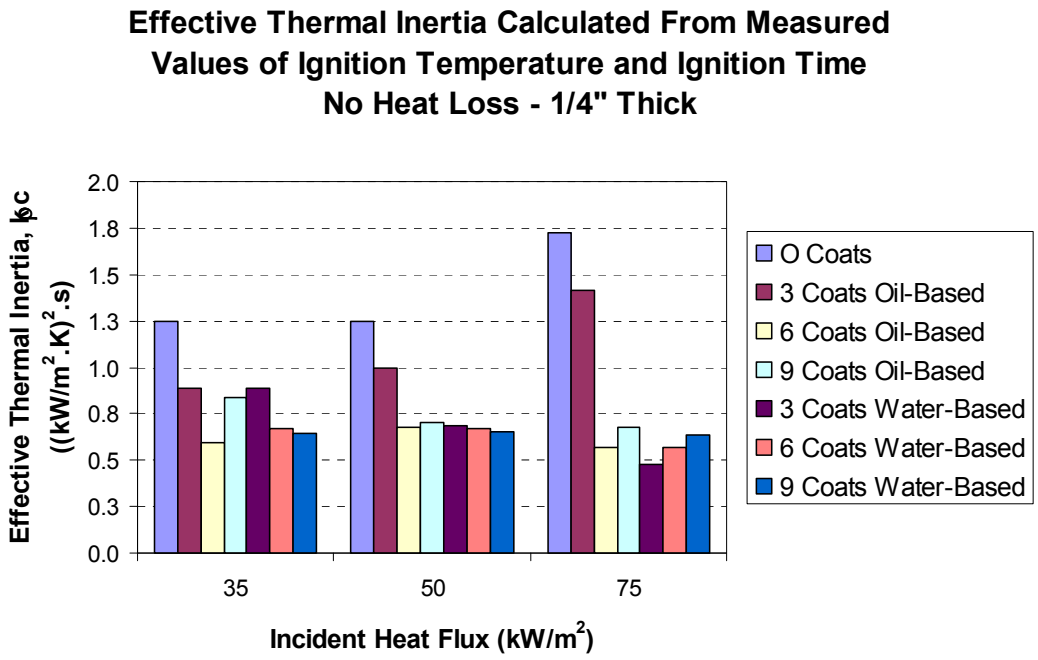

Figure 4.36 Effective Thermal Inertia From Measured Parameters for ¼ in Samples Using the "No Heat Loss" Method

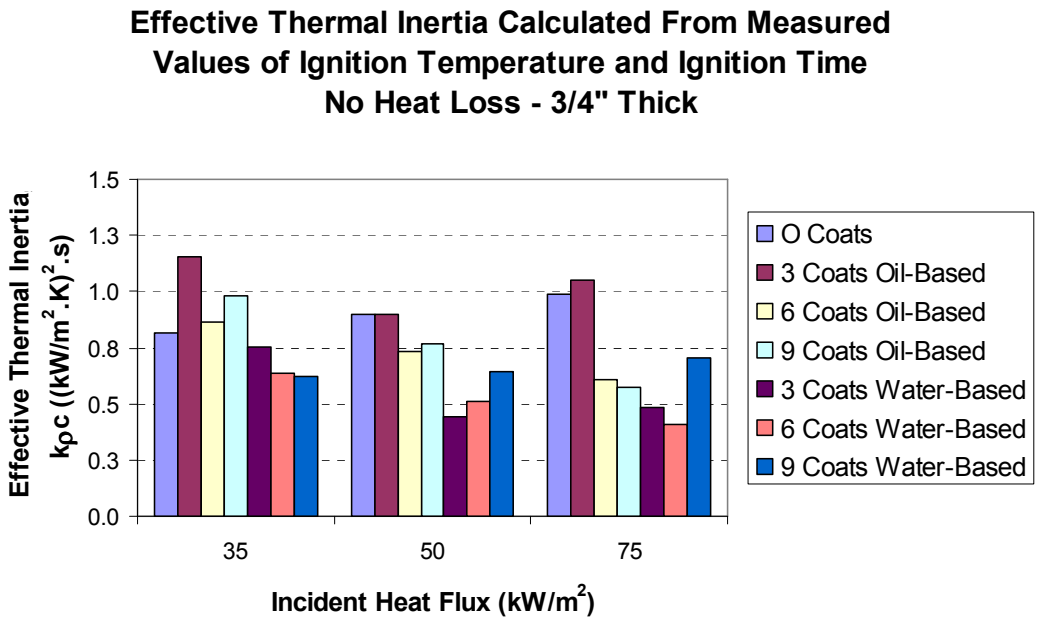

Figure 4.37 Effective Thermal Inertia From Measured Parameters for ¾ in Samples Using the "No Heat Loss" Method

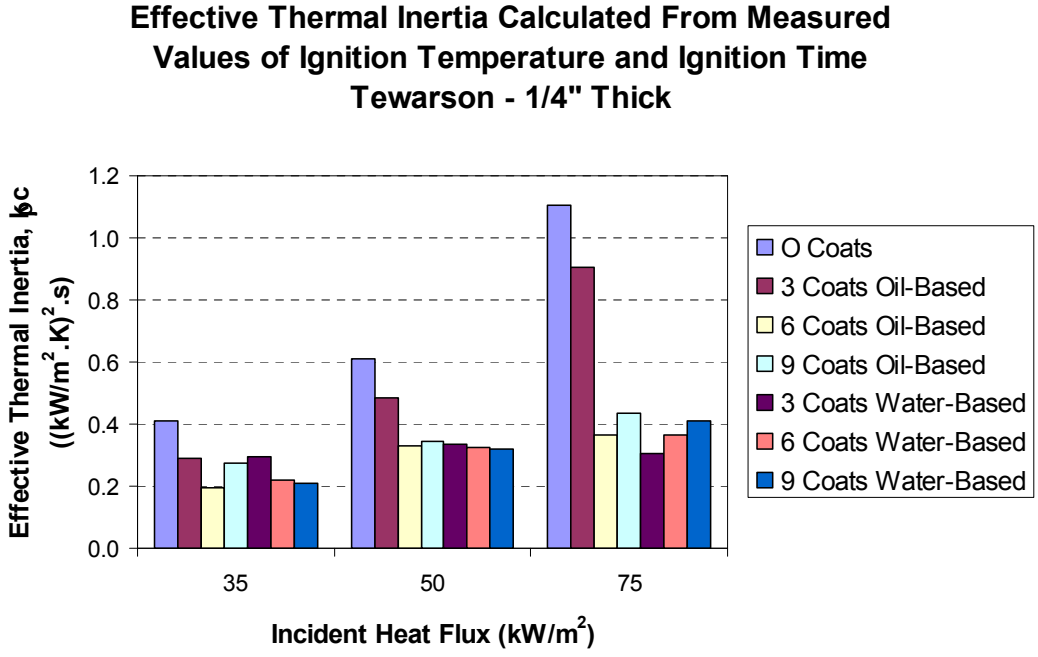

Figure 4.38 Effective Thermal Inertia From Measured Parameters for ¼ in Samples Using the "Tewarson" Method

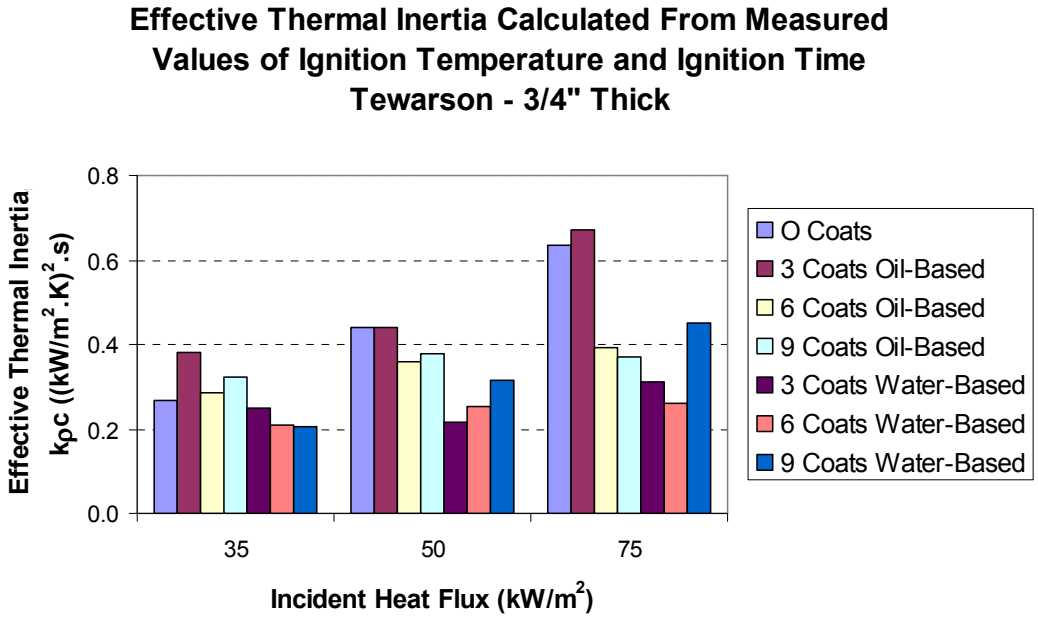

Figure 4.39 Effective Thermal Inertia From Measured Parameters for ¾ in Samples Using the "Tewarson" Method

Chapter 5. SUMMARY AND CONCLUSIONS

This study has qualitatively analyzed the effects that coatings of water-based and oil-based polyurethane have on the flammability characteristics and effective material properties for ¼ in. and ¾ in. thick oak veneer plywood by testing in the cone calorimeter. The average measured sample density for the ¼ in. plywood was found to be less than that of the ¾ in. plywood while both values encompassed the reported density for oak. The ¼ in. plywood contained a higher moisture content than the ¾ in. plywood. The application of the oil-based polyurethane was found to be easier and produced a smooth and stronger surface than the water-based polyurethane. On average, more water-based finish by mass and thickness, was applied for each coating level. During exposure to an incident heat flux in the cone calorimeter both the oil-based and water-based polyurethanes bubbled, with the water-based bubble diameters being smaller than the oil-based bubbles. No "blistering" effects that were previously reported for painted gypsum wallboard were observed. The ¼ in. samples bowed and curled significantly during testing. All samples exhibited charring and quick flame spread across the surface once ignited.

The time to ignition consistently decreased with number of coatings for each incident flux level. The ignition times for the water-based coated samples were, for the most part, slightly lower than the oil-based samples at the same imposed flux. As expected, the ignition time decreased with an increase in the incident flux. A

decrease in the time to ignition was found for an increase in the net mass of polyurethane. However, there was no consistent discernable difference in ignition times between the two finish types when related to the total mass of polyurethane. Ratios of the ignition time for the coated samples to the uncoated samples resulted in a 2 to 3 factor decrease in ignition time for the coated plywood.

Heat rate and mass loss histories were found to be repeatable for a given test parameter. The coating levels influenced the peak HRRPUA, causing it to increase as the number of coats increased. The water-based coated samples generated a higher measured peak HRRPUA for each incident heat flux value. The same was found to be true for the THRPUA. The number and type of coating also contributed to the measured average effective heat of combustion, with the water-based polyurethane coated samples measuring a higher value for each coating level. Both the type and finish levels affected the Quintiere flammability parameter. The flammability parameter was greater than zero for all test scenarios, suggesting a propensity for flame spread.

The minimum flux for ignition did not differ greatly between coating levels or finish types. However, minimum flux for the ¾ in. oak veneer plywood samples were, with the exception of the unfinished sample, consistently less (averaged 14.0 kW/m^2) than the ¼ in. plywood (averaged 15.0 kW/m^2). In general, the measured ignition temperature decreased with the number of coats for both oil-based and water-based polyurethane. Again, the type of finish had a small influence on the ignition temperature, with the values for the water-based samples being slightly higher. The plot of surface temperature histories for the different coating levels of

polyurethane suggests that the differences noticed between unfinished plywood and the different coating levels, is due to chemical rather than physical reasons. Also, if there was a physical explanation for the observations and trends between the coating levels, it would be expected that the ignition time would decrease with coating level, as was the case in the painted gypsum wallboard samples that exhibited "blistering."

The predicted ignition temperatures using the measured minimum flux for ignition were as much as 100 to 150 ºC greater than the measured temperatures. In comparison of predicted ignition times based on the ASTM E1321 methodology, the calculated values were 2 to 3 times higher than the measured value depending on whether the "No Heat Loss" or Tewarson model was used. The predicted ignition times determined using the Tewarson method were more closely related to the measured times. The effective thermal inertia values based on measured values of ignition temperatures and times to ignition were as much as 10 times more than the thermal inertia reported in the literature. The predicted values depended on whether the "No Heat Loss" or Tewarson method was used, with better agreement between measured and predicted effective thermal inertias found using the Tewarson method.

Based on the results reported here, it is apparent that the number of coats and type of finish have a significant influence on the flammability characteristics of coated plywood. Future work should include the development of an ignition model that addresses these effects.

Appendix A – Product Information

http://www.minwax.com/products/protective/

Minwax® Polycrylic® Protective Finish

Description: Polycrylic® Protective Finish is a tough, crystal clear finish that is ultra fast-drying. Its low odor formula is water-based for easy cleanup.

Description

Sheens:	Gloss, Semi-Gloss, Satin
Application tool:	synthetic bristle brush
Location:	interior wood surfaces
Dry time:	2 hours
Recoat:	after 2 hours
Cleanup:	warm water
Coverage:	125 sq. ft. per quart
Coats:	2 or 3
Recommended uses:	woodwork, cabinets, furniture, interior doors, accessories

Minwax® Polycrylic® Protective Finish is a hard, crystal clear, ultra fast-drying protective finish. It is non-flammable and has very little odor. Best of all, you can clean up with water.

This product resists damage from abrasion, scuffing, chipping, water, alcohol and other common household chemicals.

Its great clarity makes it perfect for use over any wood surface, especially over light woods (maple, ash, etc.), woods colored with water-based pastel and custom-colored stains, painted surfaces both latex and oil-based and well-bonded wall-coverings. When applying Minwax® Polycrylic® over light-colored, oil-based stains, latex and oil-based paints and wall coverings, slight ambering may occur, therefore always spot test on an inconspicuous area and let dry to ensure satisfactory results.

Use Minwax® Polycrylic® Protective Finish on furniture, trim, doors, cabinets, paneling, floors and any other interior wood surfaces. When used on floors, more frequent recoating may be required. For maximum durability on floors, we recommend Minwax® Super Fast-Drying Polyurethane for Floors or Minwax® Water-Based Polyurethane for Floors. To clean surfaces protected by Polycrylic® Protective Finish, we recommend damp wiping with a gentle cleaner such as Minwax® Wood Cleaner.

Directions

Always read the product label before use

For Interior Use Only

1. Surface must be dry and free of wax, grease, polish, old finishes in poor condition or any foreign matter.

2. Sand to a smooth, uniform surface. **DO NOT USE STEEL WOOL.** Remove dust with a cloth dampened with water or mineral spirits. Let dry completely.
   DIRECTIONS: WARNING! Removal of old paint by sanding, scraping or other means may generate dust or fumes that contain lead. Exposure to lead dust or fumes may cause brain damage or other adverse health effects, especially in children or pregnant women. Controlling exposure to lead or other hazardous substances requires the use of proper protective equipment such as a properly fitted respirator (NIOSH approved) and proper containment and cleanup. For more information, call the National Lead Information Center at 1-800-424-LEAD (in US) or contact your local health authority.

3. If desired, apply Minwax® Wood Finish™ or Minwax® Water-Based Wood Stain to unfinished interior wood surfaces following label directions. Wait at least 24 hours before applying Polycrylic® over Minwax® Wood Finish™.

4. Stir well before and regularly during use**. DO NOT SHAKE. FINISH APPEARS MILKY IN CAN BUT DRIES CRYSTAL CLEAR.**

5. Apply a thin coat of Polycrylic® with a high-quality synthetic bristle brush. Apply in one direction with the grain. Do not over brush.

6. Let dry at least 2 hours then sand with very fine sandpaper (220 grit) to ensure an even finish and proper adhesion of additional coats. Do not use steel wool. Remove all dust.

7. Apply second coat. For additional coats, repeat Step 6 before applying. Three coats are recommended.

8. After final coat, allow 3 hours before light handling and 24 hours before normal use.

Special Instructions: Polycrylic® should not be applied over red mahogany stain. Instead, use Minwax® Fast-Drying Polyurethane over any red mahogany stain.

Clean Up: Clean with soap and warm water immediately after use.

Coverage: Approximately 125 sq. ft. per quart

Notes: Thinning is not recommended. Keep from freezing. Store below 105°F. For interior use only. Dry times are based on good ventilation, temperature of 77°F, and 50% relative humidity. Lower temperature, higher humidity, lack of air movement or application of thick coats will extend drying times. Always test surface for tackiness between coats. Oil-based stains, paints or coatings applied under Polycrylic® may amber normally. Always spot test on an inconspicuous area to ensure satisfactory results.

CAUTIONS: CONTAINS ALKYL PROPANOLS, ETHYLENE GLYCOL, GLYCOL ETHERS, AND N-METHYL PYRROLIDONE. VAPOR HARMFUL. Use only with adequate ventilation. To avoid overexposure, open windows and doors or use other means to ensure fresh air entry during application and drying. If you experience eye watering, headaches or dizziness, increase fresh air or wear respiratory protection (NIOSH approved) or leave the area. Avoid contact with eyes and skin. Wash hands after using. Keep container closed when not in use.
Do not transfer contents to other containers for storage.

FIRST AID: In case of eye contact, flush thoroughly with large amounts of water for 15 minutes and get medical attention. For skin contact, wash thoroughly with soap and water. In case of respiratory difficulty, provide fresh air and call physician. If swallowed, call Poison Control Center, hospital emergency room, or physician immediately.

DELAYED EFFECTS FROM LONG-TERM OVEREXPOSURE. Contains solvents that can cause permanent brain and nervous system damage. Intentional misuse by deliberately concentrating and inhaling the contents may be harmful or fatal. WARNING: This product contains chemicals known to the State of California to cause cancer and birth defects or other reproductive harm.

DO NOT TAKE INTERNALLY. KEEP OUT OF REACH OF CHILDREN.
CONFORMS TO ASTM D-4236. Contact a physician for more health information.

Max. V.O.C. 2.3 lb/gal (275 g/L).

FAQs

Q. Why does Minwax® Polycrylic® Protective Finish appear milky in the can?

The milk-white appearance is caused by the scattering and reflection of light striking the liquid and the particles suspended in it. The slight haziness disappears on the wood leaving a clear finish.

Q. Can Polycrylic® be used over Minwax® Wood Finish™ stains?

Yes, provided the Wood Finish™ has dried completely, which generally takes 24 hours. The one exception is over Wood Finish™ Red Mahogany Stain. Polycrylic® and Red Mahogany are not compatible.

Q. When applying Polycrylic® over wood that has not been sealed with a wood stain, how can grain-raising be minimized?

Sand the wood prior to applying Polycrylic®. Before the final sanding, moisten the wood with a rag or sponge dipped in water. Allow the wood to dry, then sand off the raised grain with #220 sandpaper. After wiping off the dust, apply Polycrylic®.

Q. Can Polycrylic® Protective Finish be used over paint and wall coverings?

Yes. Polycrylic® may be applied over latex and oil-based paints and well-bonded wall coverings. Because slight ambering may occur, spot test on an inconspicuous area and let dry to ensure satisfactory results.

Q. Should Polycrylic® be sanded between coats?

Yes. A light sanding (#220 sandpaper) will remove any fine particles of dust which settle on the finish while it is still wet. Light sanding also helps abrade the surface, improving intercoat adhesion.

Q. Can steel wool be used in place of fine sandpaper?

No. Since steel wool and water can cause rust, steel wool should be avoided around all water-based wood finishing products. A stray strand lodged in the surface could leave an unsightly stain in the wood.

Q. Will water damage Polycrylic® after it has dried?

Once the resins have dried and hardened they cannot be re-dissolved by water. The dry film resists damage from water and household spills.

Minwax® Fast-Drying Polyurethane

Description: Among the most durable of protective coatings, Minwax® Fast-Drying Polyurethane offers exceptionally long-lasting beauty on both finished and unfinished wood.

Description

Sheens:	Gloss, Semi-Gloss, Satin
Application tool:	natural bristle brush, foam brush, or lambswool applicator
Location:	interior wood surfaces
Recoat:	after 4-6 hours
Cleanup:	mineral spirits or paint thinner
Coverage:	125 sq. ft. per quart
Coats:	2-3
Recommended uses:	furniture, doors, cabinets and floors

DESCRIPTION: Minwax® Fast-Drying Polyurethane is a clear, hard finish that dries fast to protect and beautify interior wood surfaces such as furniture, cabinets, molding, and doors. Minwax® Fast-Drying Polyurethane's long-lasting protective finish makes it ideal for use on hardwood, softwood, and parquet. For exterior wood surfaces, we recommend Minwax® Helmsman® Spar Urethane. For floor projects, you may want to consider the added benefits found in Minwax® Super Fast-Drying Polyurethane for Floors.

Directions

Always read the product label before use

WARNING: Removal of old paint by sanding, scraping or other means may generate dust or fumes that contain lead. Exposure to lead dust or fumes may cause brain damage or other adverse health effects, especially in children or pregnant women. Controlling exposure to lead or other hazardous substances requires the use of proper protective equipment, such as properly fitted respirator (NIOSH approved) and proper containment and cleanup. For more information, call the National Lead Information Center at 1-800-424-LEAD (in US) or contact your local health authority.

DIRECTIONS:

1. Surface must be dry and free of old finishes in poor condition, paint, wax, grease, polish, dirt or other foreign matter.
2. Sand to obtain a smooth uniform surface. Remove all dust with a cloth dampened with mineral spirits.
3. Stir Minwax® Fast-Drying Polyurethane before and during use to eliminate settling on the bottom of the can. Stir in such a manner as to rotate the product from the bottom to the top of the can. NEVER SHAKE.
4. Apply a THIN coat of Minwax® Fast-Drying Polyurethane using a high-quality natural or foam brush.
5. Let dry 3-4 hours. Then lightly sand entire surface with fine sand-paper (220 grit) to ensure an even finish and proper adhesion. Remove all dust.
6. Apply second coat. If third coat is desired, repeat step 5 before application.
7. After final coat, allow 24 hours before light use.

When used on wooden floors, use a lambswool or synthetic pad applicator or natural bristle brush and maintain a wet edge to avoid lap marks. For maximum durability, we recommend three coats. Avoid heavy traffic and replacing of furniture for 72 hours after final coat. When replacing furniture, do not slide. Do not install rugs or clean floors for 7 days.

CLEAN-UP: For easy clean-up use mineral spirits or paint thinner.
COVERAGE: Approximately 80 square feet per pint.

Note: Above dry times are based on good ventilation, temperature of 77°F and 50% relative humidity. Lower temperature, higher humidity, lack of air movement or application of thick coats will extend drying times. Always test tackiness between coats. Do not sand or re-coat when surface is tacky. Slight ambering may be experienced when Polyurethane is applied over light-colored wood surfaces. Always spot test in an inconspicuous area to ensure satisfactory results. For light-colored wood surfaces, we recommend protecting with Minwax® Polycrylic® Protective Finish.
.

CAUTIONS: CONTAINS: ALIPHATIC HYDROCARBONS. Contents are **COMBUSTIBLE.** Keep away from heat and open flame. **VAPOR HARMFUL.** Use with adequate ventilation. To avoid overexposure, open windows and doors or use other means to ensure fresh air entry during application and drying. If you experience eye watering, headaches or dizziness, increase fresh air or wear respiratory protection (NIOSH approved), or leave the area. Avoid contact with eyes or skin. Wash hands after using. Keep container closed when not in use. Do not transfer contents to other containers for storage.

FIRST AID: In case of eye contact, flush thoroughly with large amounts of water for 15 minutes and get medical attention. For skin contact, wash thoroughly with soap and water. In case of respiratory difficulty, provide fresh air and call physician. If swallowed, call Poison Control Center, hospital emergency room, or physician immediately.

NOTICE: Reports have associated repeated and prolonged occupational exposre to solvents with permanent brain and nervous system damage. Intentional misuse by deliberately concentrating and inhaling contents can be harmful or fatal.

Warning: This product contains a chemical known to the State of California to cause cancer and birth defects or other reproductive harm.

DO NOT TAKE INTERNALLY. KEEP OUT OF REACH OF CHILDREN.

FAQs

Q. What is the best way to select a sheen?

Sheen choice is a personal preference. Satin sheens reflect less light and gloss sheens reflect more light.

Q. Is one sheen more durable than the others?

No. The additives which distinguish satin from semi-gloss and gloss do not compromise the durability of the finish.

Q. What can be done to avoid bubbles in the finish?

There are four ways. First, stir, don't shake, the can. Second, use a high-quality, natural bristle brush. Third, work the finish into the wood, but don't create excess foam. Fourth, "tip-off" the finish before stopping, carefully running the brush at a 45-degree angle the length of each board in one unbroken movement. This will burst and smooth out any bubbles that may have been created

Q. Should Minwax® Fast-Drying Polyurethane be sanded between coats?

Yes. A light sanding (#220 sandpaper) will remove any fine particles of dust which have settled on the finish while it was still wet. Light sanding also helps abrade the surface, improving intercoat adhesion.

Q. Why does Minwax® Fast-Drying Polyurethane sometimes take longer to dry than the instructions indicate?
The drying time is affected by the amount of moisture in the air, the air temperature and the thickness of the coats. When humidity is high, temperature is low, or coats are thick, it takes longer for the film to dry.

Q. What is the best way to determine how many coats of Minwax® Fast-Drying Polyurethane to apply?

If you look closely at the wood in bright, direct light, you should not be able to detect any dry spots. If you do, an additional coat is necessary to protect the wood.

Q. Can Minwax® Fast-Drying Polyurethane be applied over Minwax® Tung Oil Finish or Minwax® Antique Oil Finish?

Yes, but make sure the oil has had at least 24 hours to totally dry, and sand lightly to ensure good adhesion.

Q. Does Minwax® Fast-Drying Polyurethane need to be waxed?

No. Wax does provide an extra layer of protection, but it will prevent you from applying an additional coat of Minwax® Fast-Drying Polyurethane in the future without first removing the wax. Instead, we recommend using Minwax® Wood Cleaner to keep wood clean and looking beautiful.

Appendix B – Sample Mass Data

1/4 INCH (6.35 MM) THICK OAK PLYWOOD COATED WITH OIL-BASED PU

Test #	mass (g) 0 Coats	mass (g) 0 Coats	mass (g) PU added 1st coat	mass (g) PU added 2nd coat	mass (g) PU added 3rd coat	mass (g) PU added 4th coat	mass (g) PU added 5th coat	mass (g) PU added 6th coat	mass (g) PU added 7th coat	mass (g) PU added 8th coat	mass (g) PU added 9th coat	mass (g) Total PU added
0-1-35	28.85	28.85										n/a
0-2-35	27.15	27.20										n/a
0-3-35	26.65	26.60										n/a
0-4-50	28.35	28.30										n/a
0-5-50	25.25	25.20										n/a
0-6-50	26.50	26.45										n/a
0-7-75	29.00	28.95										n/a
0-8-75	28.45	28.45										n/a
0-9-75	28.45	28.45										n/a
3-1-35	26.40	26.35	0.75	0.40	0.25							1.40
3-2-35	24.90	24.95	0.75	0.40	0.35							1.50
3-3-35	24.95	24.95	0.75	0.45	0.30							1.50
3-4-50	25.50	25.45	0.70	0.45	0.30							1.45
3-5-50	25.25	25.20	0.70	0.40	0.35							1.45
3-6-50	27.00	27.00	0.65	0.45	0.40							1.50
3-7-75	27.45	27.45	0.65	0.45	0.40							1.50
3-8-75	28.80	28.80	0.55	0.35	0.35							1.25
3-9-75	26.55	26.50	0.65	0.35	0.40							1.40

6-1-35	27.25	27.25	0.60	0.45	0.30	0.30	0.40	0.45				2.50
6-2-35	27.15	27.05	0.75	0.45	0.25	0.25	0.35	0.45				2.50
6-3-35	27.70	27.70	0.65	0.45	0.30	0.30	0.35	0.50				2.55
6-4-50	27.10	27.05	0.65	0.35	0.30	0.35	0.45	0.35				2.45
6-5-50	27.25	27.20	0.75	0.35	0.30	0.30	0.35	0.40				2.45
6-6-50	29.00	28.95	0.65	0.40	0.30	0.40	0.30	0.40				2.45
6-7-75	26.75	26.70	0.70	0.35	0.30	0.45	0.35	0.45				2.60
6-8-75	28.25	28.15	0.65	0.40	0.35	0.35	0.40	0.40				2.55
6-9-75	24.45	24.35	0.65	0.40	0.30	0.35	0.35	0.40				2.45
9-1-35	25.20	25.20	0.75	0.35	0.35	0.25	0.35	0.40	0.40	0.25	0.50	3.60
9-2-35	28.25	28.20	0.75	0.30	0.30	0.35	0.30	0.45	0.35	0.25	0.50	3.55
9-3-35	26.10	26.05	0.65	0.45	0.30	0.30	0.40	0.35	0.30	0.40	0.45	3.60
9-4-50	25.70	25.65	0.70	0.40	0.25	0.35	0.40	0.35	0.35	0.35	0.45	3.60
9-5-50	26.30	26.35	0.55	0.40	0.25	0.40	0.30	0.35	0.30	0.40	0.45	3.40
9-6-50	25.25	25.25	0.65	0.35	0.30	0.35	0.35	0.35	0.30	0.45	0.40	3.50
9-7-75	27.05	27.05	0.65	0.35	0.30	0.35	0.35	0.35	0.35	0.35	0.45	3.50
9-8-75	27.70	27.65	0.70	0.40	0.35	0.30	0.40	0.35	0.35	0.40	0.40	3.65
9-9-75	27.20	27.20	0.65	0.35	0.35	0.30	0.35	0.40	0.30	0.40	0.40	3.50
AVERAGE	26.92	26.89	0.68	0.39	0.32	0.33	0.36	0.40	0.33	0.36	0.44	2.49
STDEV	1.30	1.30	0.06	0.04	0.04	0.05	0.04	0.05	0.04	0.07	0.04	0.88

3/4 INCH (19.05 MM) THICK OAK PLYWOOD COATED WITH OIL-BASED PU

Test #	mass (g) 0 Coats	mass (g) 0 Coats	mass (g) PU added 1st coat	mass (g) PU added 2nd coat	mass (g) PU added 3rd coat	mass (g) PU added 4th coat	mass (g) PU added 5th coat	mass (g) PU added 6th coat	mass (g) PU added 7th coat	mass (g) PU added 8th coat	mass (g) PU added 9th coat	mass (g) Total PU added
0-1-35	107.20	107.10										n/a
0-2-35	102.80	102.70										n/a
0-3-35	109.55	109.45										n/a
0-4-50	103.85	103.70										n/a
0-5-50	105.90	105.75										n/a
0-6-50	105.30	105.15										n/a
0-7-75	104.35	104.15										n/a
0-8-75	108.70	108.50										n/a
0-9-75	110.70	110.65										n/a
3-1-35	106.25	105.95	0.55	0.60	0.40							1.55
3-2-35	108.20	108.00	0.65	0.60	0.35							1.60
3-3-35	104.30	104.15	0.70	0.55	0.45							1.70
3-4-50	104.85	104.70	0.60	0.60	0.40							1.60
3-5-50	108.40	108.25	0.60	0.60	0.35							1.55
3-6-50	114.20	114.05	0.70	0.50	0.35							1.55
3-7-75	106.30	106.25	0.80	0.55	0.30							1.65
3-8-75	112.65	112.60	0.55	0.65	0.35							1.55
3-9-75	107.40	107.45	0.60	0.55	0.20							1.35

6-1-35	105.50	105.40	0.80	0.65	0.35	0.20	0.40	0.20				2.60
6-2-35	108.30	108.15	0.75	0.65	0.30	0.25	0.35	0.30				2.60
6-3-35	112.90	112.80	0.60	0.65	0.35	0.30	0.25	0.35				2.50
6-4-50	106.70	106.65	0.65	0.65	0.20	0.30	0.30	0.35				2.45
6-5-50	104.80	104.75	0.75	0.60	0.30	0.30	0.30	0.30				2.55
6-6-50	103.45	103.35	0.70	0.60	0.30	0.30	0.30	0.40				2.60
6-7-75	108.85	108.80	0.75	0.70	0.25	0.30	0.25	0.45				2.70
6-8-75	104.80	104.75	0.70	0.70	0.30	0.20	0.30	0.35				2.55
6-9-75	104.60	104.60	0.65	0.70	0.25	0.20	0.20	0.40				2.40
9-1-35	110.30	110.25	0.65	0.65	0.30	0.30	0.35	0.45	0.45	0.15	0.50	3.80
9-2-35	103.90	103.80	0.80	0.60	0.35	0.30	0.45	0.35	0.40	0.25	0.45	3.95
9-3-35	104.55	104.50	0.90	0.55	0.40	0.25	0.35	0.50	0.30	0.25	0.50	4.00
9-4-50	108.15	108.15	0.80	0.55	0.30	0.30	0.35	0.55	0.30	0.20	0.50	3.85
9-5-50	105.40	105.45	0.70	0.55	0.35	0.30	0.35	0.50	0.25	0.25	0.45	3.70
9-6-50	108.55	108.55	0.75	0.60	0.40	0.15	0.50	0.40	0.30	0.40	0.40	3.90
9-7-75	107.70	107.65	0.75	0.55	0.45	0.15	0.45	0.40	0.35	0.45	0.25	3.80
9-8-75	108.70	108.65	0.80	0.65	0.35	0.20	0.45	0.35	0.30	0.30	0.40	3.80
9-9-75	103.40	103.35	0.80	0.60	0.35	0.10	0.40	0.45	0.25	0.35	0.15	3.45
AVERAGE	106.98	106.89	0.71	0.61	0.33	0.24	0.35	0.39	0.32	0.29	0.40	2.64
STDEV	2.84	2.84	0.09	0.05	0.06	0.07	0.08	0.08	0.07	0.10	0.12	0.94

1/4 INCH (6.35 MM) THICK OAK PLYWOOD COATED WITH WATER-BASED PU

Test #	mass (g) 0 Coats	mass (g) 0 Coats	mass (g) PU added 1st coat	mass (g) PU added 2nd coat	mass (g) PU added 3rd coat	mass (g) PU added 4th coat	mass (g) PU added 5th coat	mass (g) PU added 6th coat	mass (g) PU added 7th coat	mass (g) PU added 8th coat	mass (g) PU added 9th coat	mass (g) Total PU added
0-1-35-w	28.05	28.05										n/a
0-2-35-w	28.20	28.20										n/a
0-3-35-w	25.20	25.15										n/a
0-4-50-w	28.60	28.65										n/a
0-5-50-w	26.75	26.75										n/a
0-6-50-w	26.95	26.95										n/a
0-7-75-w	25.55	25.60										n/a
0-8-75-w	27.95	27.95										n/a
0-9-75-w	26.45	26.45										n/a
3-1-35-w	26.55	26.60	0.95	0.60	0.50							2.05
3-2-35-w	25.30	25.35	0.80	0.60	0.50							1.90
3-3-35-w	26.00	26.10	0.75	0.55	0.50							1.80
3-4-50-w	25.50	25.55	0.60	0.55	0.55							1.70
3-5-50-w	25.25	25.20	1.00	0.55	0.60							2.15
3-6-50-w	25.45	25.50	1.05	0.65	0.50							2.20
3-7-75-w	26.75	26.80	0.65	0.70	0.55							1.90
3-8-75-w	26.35	26.35	0.85	0.60	0.50							1.95
3-9-75-w	27.85	27.90	0.70	0.65	0.55							1.90

6-1-35-w	25.75	25.80	0.70	0.50	0.60	0.65	0.50	0.50				3.45
3-2-35-w	25.45	25.45	0.65	0.40	0.65	0.55	0.60	0.60				3.45
6-3-35-w	29.30	29.30	0.60	0.55	0.35	0.50	0.55	0.55				3.10
6-4-50-w	26.80	26.85	0.65	0.50	0.65	0.45	0.55	0.50				3.30
6-5-50-w	29.20	29.15	0.70	0.55	0.40	0.40	0.55	0.50				3.10
6-6-50-w	28.50	28.55	0.70	0.50	0.45	0.35	0.60	0.50				3.10
6-7-75-w	26.50	26.60	0.70	0.55	0.45	0.45	0.70	0.50				3.35
6-8-75-w	25.40	25.40	0.70	0.45	0.50	0.55	0.60	0.55				3.35
6-9-75-w	28.05	28.00	0.85	0.55	0.50	0.45	0.55	0.50				3.40
9-1-35-w	27.65	27.65	0.60	0.30	0.40	0.60	0.45	0.50	0.50	0.55	0.50	4.40
9-2-35-w	28.15	28.20	0.55	0.20	0.45	0.55	0.35	0.55	0.45	0.55	0.50	4.15
9-3-35-w	27.90	27.95	0.60	0.20	0.45	0.55	0.45	0.45	0.25	0.60	0.50	4.05
9-4-50-w	28.30	28.25	0.50	0.25	0.50	0.50	0.45	0.50	0.50	0.55	0.55	4.30
9-5-50-w	26.70	26.65	0.60	0.25	0.40	0.50	0.45	0.50	0.45	0.60	0.50	4.25
9-6-50-w	28.25	28.30	0.55	0.25	0.45	0.60	0.45	0.55	0.40	0.50	0.65	4.40
9-7-75-w	28.30	28.30	0.50	0.20	0.45	0.55	0.35	0.50	0.50	0.55	0.45	4.05
9-8-75-w	26.45	26.45	0.65	0.15	0.55	0.55	0.40	0.50	0.45	0.50	0.60	4.35
9-9-75-w	27.85	27.85	0.55	0.30	0.45	0.55	0.45	0.50	0.45	0.50	0.55	4.30
AVERAGE	27.03	27.05	0.69	0.45	0.50	0.52	0.50	0.51	0.44	0.54	0.53	3.16
STDEV	1.24	1.23	0.14	0.17	0.07	0.07	0.09	0.03	0.08	0.04	0.06	0.97

3/4 INCH (19.05 MM) THICK OAK PLYWOOD COATED WITH WATER-BASED PU

Test #	mass (g) 0 Coats	mass (g) 0 Coats	mass (g) PU added 1st coat	mass (g) PU added 2nd coat	mass (g) PU added 3rd coat	mass (g) PU added 4th coat	mass (g) PU added 5th coat	mass (g) PU added 6th coat	mass (g) PU added 7th coat	mass (g) PU added 8th coat	mass (g) PU added 9th coat	mass (g) Total PU added
0-1-35-w	107.80	107.90										n/a
0-2-35-w	108.30	108.45										n/a
0-3-35-w	106.20	106.25										n/a
0-4-50-w	105.50	105.55										n/a
0-5-50-w	106.70	106.70										n/a
0-6-50-w	108.35	108.40										n/a
0-7-75-w	103.70	103.75										n/a
0-8-75-w	103.35	103.40										n/a
0-9-75-w	114.50	114.65										n/a
3-1-35-w	104.60	104.80	1.15	0.40	0.50							2.05
3-2-35-w	103.90	103.95	0.75	0.65	0.50							1.90
3-3-35-w	104.40	104.45	0.75	0.60	0.55							1.90
3-4-50-w	110.50	110.55	0.60	0.70	0.55							1.85
3-5-50-w	108.90	108.95	0.70	0.60	0.55							1.85
3-6-50-w	105.45	105.40	1.00	0.70	0.45							2.15
3-7-75-w	101.55	101.60	1.00	0.65	0.50							2.15
3-8-75-w	104.15	104.20	0.80	0.55	0.65							2.00
3-9-75-w	109.25	109.25	0.55	0.55	0.60							1.70

6-1-35-w	104.40	104.60	0.70	0.40	0.50	0.65	0.50	0.40				3.15
3-2-35-w	106.95	107.00	0.65	0.55	0.55	0.45	0.55	0.50				3.25
6-3-35-w	106.00	106.10	0.75	0.45	0.50	0.20	0.55	0.45				2.90
6-4-50-w	109.50	109.60	0.65	0.45	0.55	0.20	0.70	0.45				3.00
6-5-50-w	105.95	106.00	0.70	0.45	0.70	0.20	0.50	0.50				3.05
6-6-50-w	107.50	107.60	0.75	0.45	0.50	0.55	0.50	0.55				3.30
6-7-75-w	107.25	107.30	0.75	0.45	0.65	0.60	0.50	0.45				3.40
6-8-75-w	107.10	107.15	0.75	0.45	0.50	0.65	0.55	0.45				3.35
6-9-75-w	104.80	104.85	0.65	0.45	0.55	0.60	0.55	0.35				3.15
9-1-35-w	103.30	103.55	0.85	0.20	0.70	0.50	0.40	0.50	0.35	0.40	0.45	4.35
9-2-35-w	102.85	103.00	0.75	0.20	0.65	0.50	0.50	0.40	0.45	0.50	0.45	4.40
9-3-35-w	106.80	106.90	0.75	0.20	0.65	0.55	0.45	0.40	0.45	0.45	0.55	4.45
9-4-50-w	109.30	109.35	0.55	0.25	0.60	0.55	0.45	0.50	0.30	0.45	0.50	4.15
9-5-50-w	104.70	104.80	0.70	0.35	0.35	0.65	0.40	0.60	0.30	0.55	0.55	4.45
9-6-50-w	103.20	103.35	0.75	0.25	0.60	0.65	0.40	0.55	0.20	0.55	0.50	4.45
9-7-75-w	105.60	105.70	0.65	0.30	0.55	0.55	0.45	0.50	0.35	0.50	0.50	4.35
9-8-75-w	102.00	102.05	0.80	0.20	0.60	0.45	0.50	0.45	0.40	0.50	0.45	4.35
9-9-75-w	103.95	104.05	0.70	0.45	0.60	0.65	0.40	0.45	0.60	0.50	0.35	4.70
AVERAGE	106.06	106.14	0.75	0.44	0.56	0.51	0.49	0.47	0.38	0.49	0.48	3.18
STDEV	2.68	2.68	0.13	0.16	0.08	0.16	0.08	0.06	0.11	0.05	0.06	1.03

Appendix C – Ignition Temperature Data

3/4" Thick Samples							
Sample #	**# Coats**	**PU**	**Thickness** (mm)	**Mass** (g)	q_{ext} (kW/m^2)	t_{ig} (s)	T_{ig} (^oC)
5	0	oil	18.07	102.50	35	40.08	309.06
6	0	oil	17.90	95.51	50	24.28	315.95
7	0	oil	17.86	98.72	75	13.21	331.05
20	3	oil	18.08	95.83	35	34.84	275.50
21	3	oil	18.03	92.70	50	21.96	286.94
22	3	oil	18.28	94.08	75	12.68	281.34
35	6	oil	18.32	100.32	35	33.24	277.03
36	6	oil	18.21	97.17	50	21.46	252.87
37	6	oil	18.39	97.79	75	10.86	279.84
51	9	oil	18.40	101.04	35	32.56	292.93
52	9	oil	18.39	100.77	50	15.52	275.33
53	9	oil	18.31	96.09	75	7.14	213.83
65	3	water	18.16	96.82	35	52.67	300.10
66	3	water	18.16	95.08	50	24.24	299.02
67	3	water	18.17	93.21	75	8.30	303.12
81	6	water	18.62	98.26	35	35.20	303.36
82	6	water	18.24	95.75	50	19.17	289.41
83	6	water	18.31	95.15	75	7.86	261.97
95	9	water	18.51	98.97	35.00	33.86	276.50
96	9	water	18.34	92.90	50.00	18.90	287.03
97	9	water	18.32	95.91	75.00	8.70	256.58

1/4" Thick Samples							
Sample #	**# Coats**	**PU**	**Thickness** (mm)	**Mass** (g)	**q_{ext}** (kW/m^2)	**t_{ig}** (s)	**T_{ig}** (^oC)
6	0	oil	5.34	25.26	75	10.61	297.75
7	0	oil	5.35	25.71	50	21.56	235.62
8	0	oil	5.36	26.62	75	37.37	232.75
19	3	oil	5.38	25.58	75	9.27	275.66
20	3	oil	5.45	27.02	50	17.59	255.01
21	3	oil	5.50	25.97	35	31.99	289.39
34	6	oil	5.48	27.88	75	10.14	276.02
35	6	oil	5.49	27.54	50	19.46	322.96
36	6	oil	5.47	27.94	35	30.71	309.97
49	9	oil	5.62	28.29	75	6.21	193.33
50	9	oil	5.58	28.87	50	19.61	287.73
51	9	oil	5.66	26.78	35	26.98	266.69
64	3	water	5.47	27.4	75.00	13.90	394.2
65	3	water	5.39	26.7	50.00	18.52	267.8
66	3	water	5.42	26.2	35.00	33.30	281.4
67	3	water	5.53	27.7	50.00	18.87	269.4
79	6	water	5.52	28.7	75.00	9.49	247.1
80	6	water	5.61	26.7	50.00	17.52	286.7
81	6	water	5.71	28.8	35.00	39.02	301.2
94	9	water	5.80	28.24	75.00	8.24	251.86
96	9	water	5.68	29.24	35.00	32.62	287.68
97	9	water	5.84	29.12	50.00	15.05	254.58

Analysis of Ignition Temperature Data							
Thickness (Inches)	**# Coats**	**PU**	**t_{ig}** (s)	**AVG T_{ig}** (^{o}C)	**MIN T_{ig}** (^{o}C)	**MAX T_{ig}** (^{o}C)	**STDEV T_{ig}** (^{o}C)
3/4	0	N/A	40.08	318.69	309.06	331.05	11.25
3/4	3	oil	12.68	281.26	275.50	286.94	8.09
3/4	6	oil	33.24	269.91	252.87	279.84	14.83
3/4	9	oil	7.14	260.70	213.83	292.93	41.53
3/4	3	water	52.67	300.75	299.02	303.12	2.13
3/4	6	water	7.86	284.91	261.97	303.36	21.06
3/4	9	water	8.70	273.37	256.58	287.03	15.46
1/4	0	N/A	40.08	255.37	232.75	297.75	36.73
1/4	3	oil	12.68	273.35	255.01	289.39	17.31
1/4	6	oil	33.24	302.98	276.02	322.96	24.24
1/4	9	oil	7.14	249.25	193.33	287.73	49.56
1/4	3	water	52.67	303.22	267.83	394.24	60.98
1/4	6	water	7.86	278.33	247.09	301.17	28.00
1/4	9	water	8.70	264.71	251.86	287.68	19.94

Appendix D – Sample Data

¼" Samples

Sample	Sample #	Coats of PU	PU Type	q''_{ext} (kW/m^2)	m_{PU} (g)	m_{Total} (g)	Thickness (mm)	A_{Total} (cm^2)
1	0-1-35-025	0	oil	35	n/a	28.80	5.28	103.53
2	0-2-35-025	0	oil	35	n/a	27.15	5.37	103.02
3	0-3-35-025	0	oil	35	n/a	26.59	5.29	103.53
4	0-4-50-025	0	oil	50	n/a	28.30	5.32	103.53
5	0-5-50-025	0	oil	50	n/a	25.20	5.28	101.51
6	0-6-50-025	0	oil	50	n/a	26.42	5.35	103.02
7	0-7-75-025	0	oil	75	n/a	28.88	5.27	103.02
8	0-8-75-025	0	oil	75	n/a	28.35	5.25	103.02
9	0-9-75-025	0	oil	75	n/a	28.29	5.30	102.52
10	3-1-35-025	3	oil	35	1.40	27.67	5.32	103.53
11	3-2-35-025	3	oil	35	1.50	26.35	5.39	103.02
12	3-3-35-025	3	oil	35	1.50	26.33	5.33	103.53
13	3-4-50-025	3	oil	50	1.45	26.83	5.34	103.53
14	3-5-50-025	3	oil	50	1.45	26.55	5.37	103.02
15	3-6-50-025	3	oil	50	1.50	28.32	5.34	102.52
16	3-7-75-025	3	oil	75	1.50	28.77	5.22	103.02
17	3-8-75-025	3	oil	75	1.25	29.78	5.37	102.52
18	3-9-75-025	3	oil	75	1.40	27.72	5.25	103.53
19	6-1-35-025	6	oil	35	2.50	29.59	5.55	103.02
20	6-2-35-025	6	oil	35	2.50	29.45	5.53	103.02
21	6-3-35-025	6	oil	35	2.55	30.13	5.56	103.53
22	6-4-50-025	6	oil	50	2.45	29.39	5.49	103.02
23	6-5-50-025	6	oil	50	2.45	29.56	5.42	103.02
24	6-6-50-025	6	oil	50	2.45	31.27	5.49	103.53
25	6-7-75-025	6	oil	75	2.60	29.18	5.28	104.04
26	6-8-75-025	6	oil	75	2.55	30.49	5.37	104.04
27	6-10-75-025	6	oil	75	2.75	30.06	5.58	102.51
28	9-2-35-025	9	oil	35	3.55	31.65	5.53	103.02
29	9-3-35-025	9	oil	35	3.60	29.62	5.34	103.53
30	9-4-50-025	9	oil	50	3.60	29.15	5.40	103.53
31	9-5-50-025	9	oil	50	3.40	29.62	5.51	103.53
32	9-6-50-025	9	oil	50	3.50	28.64	5.54	103.02
33	9-7-75-025	9	oil	75	3.50	30.51	5.56	103.02
34	9-8-75-025	9	oil	75	3.65	31.21	5.46	103.02
35	9-9-75-025	9	oil	75	3.50	30.61	5.47	103.53
36	9-10-35-025	9	oil	35	3.65	30.30	5.50	103.53

¼” Samples

Sample	Sample #	Coats of PU	PU Type	q''_{ext} (kW/m^2)	m_{PU} (g)	m_{Total} (g)	Thickness (mm)	A_{Total} (cm^2)
37	0-1-35-025-w	0	water	35	n/a	27.90	5.16	103.02
38	0-2-35-025-w	0	water	35	n/a	28.05	5.35	103.02
39	0-3-35-025-w	0	water	35	n/a	25.05	5.26	103.53
40	0-4-50-025-w	0	water	50	n/a	28.41	5.25	103.02
41	0-5-50-025-w	0	water	50	n/a	26.60	5.31	103.53
42	0-6-50-025-w	0	water	50	n/a	26.83	5.27	103.02
43	0-7-75-025-w	0	water	75	n/a	25.46	5.15	103.53
44	0-8-75-025-w	0	water	75	n/a	27.77	5.36	104.04
45	0-9-75-025-w	0	water	75	n/a	26.33	5.15	102.01
46	3-1-35-025-w	3	water	35	2.05	28.29	5.34	103.02
47	3-2-35-025-w	3	water	35	1.90	26.86	5.41	102.52
48	3-3-35-025-w	3	water	35	1.80	27.56	5.27	103.02
49	3-4-50-025-w	3	water	50	1.70	26.90	5.38	103.02
50	3-5-50-025-w	3	water	50	2.15	26.92	5.31	102.52
51	3-6-50-025-w	3	water	50	2.20	27.33	5.34	103.02
52	3-7-75-025-w	3	water	75	1.90	28.36	5.48	103.02
53	3-8-75-025-w	3	water	75	1.95	27.98	5.34	103.53
54	3-9-75-025-w	3	water	75	1.90	29.47	5.42	103.02
55	6-1-35-025-w	6	water	35	3.45	28.89	5.40	102.52
56	6-2-35-025-w	6	water	35	3.45	28.48	5.47	102.52
57	6-3-35-025-w	6	water	35	3.10	32.22	5.49	103.02
58	6-4-50-025-w	6	water	50	3.30	29.91	5.59	103.02
59	6-5-50-025-w	6	water	50	3.10	32.05	5.61	103.53
60	6-6-50-025-w	6	water	50	3.10	31.53	5.60	103.02
61	6-7-75-025-w	6	water	75	3.35	29.60	5.38	103.53
62	6-8-75-025-w	6	water	75	3.35	28.43	5.46	103.02
63	6-9-75-025-w	6	water	75	3.40	31.10	5.24	103.53
64	9-1-35-025-w	9	water	35	4.40	31.70	5.28	103.02
65	9-2-35-025-w	9	water	35	4.15	32.11	5.56	104.04
66	9-3-35-025-w	9	water	35	4.05	31.75	5.63	102.52
67	9-4-50-025-w	9	water	50	4.30	32.29	5.69	103.02
68	9-5-50-025-w	9	water	50	4.25	30.67	5.63	102.52
69	9-6-50-025-w	9	water	50	4.40	32.44	5.63	102.52
70	9-7-75-025-w	9	water	75	4.05	32.10	5.37	102.52
71	9-8-75-025-w	9	water	75	4.35	30.48	5.66	102.52
72	9-9-75-025-w	9	water	75	4.30	31.84	5.29	102.52

¼” Samples

Sample	Sample #	Volume (m^3)	Density (kg/m^3)	Application Rate (g/m^2/coat)	t_{ig} (s)	HRRPUA Peak (kW/m^2)	HOC Average (MJ/kg)
1	0-1-35-025	5.47E-05	526.86	n/a	40	248.12	10.53
2	0-2-35-025	5.53E-05	490.75	n/a	42	259.76	10.86
3	0-3-35-025	5.48E-05	485.51	n/a	39	244.21	10.64
4	0-4-50-025	5.51E-05	513.82	n/a	23	354.84	11.03
5	0-5-50-025	5.36E-05	470.20	n/a	21	351.33	11.57
6	0-6-50-025	5.51E-05	479.34	n/a	19	352.09	11.11
7	0-7-75-025	5.43E-05	531.93	n/a	14	423.68	11.22
8	0-8-75-025	5.41E-05	524.16	n/a	15	443.57	11.13
9	0-9-75-025	5.43E-05	520.68	n/a	14	468.01	11.26
10	3-1-35-025	5.51E-05	502.38	45.08	37	376.59	11.45
11	3-2-35-025	5.55E-05	474.53	48.53	33	390.75	11.31
12	3-3-35-025	5.52E-05	477.15	48.30	39	400.56	11.33
13	3-4-50-025	5.53E-05	485.30	46.69	16	507.55	11.71
14	3-5-50-025	5.53E-05	479.91	46.92	20	518.97	12.26
15	3-6-50-025	5.47E-05	517.33	48.77	24	481.65	11.70
16	3-7-75-025	5.38E-05	534.98	48.53	14	---	---
17	3-8-75-025	5.51E-05	540.96	40.64	14	564.84	11.57
18	3-9-75-025	5.44E-05	510.00	45.08	10	582.39	12.01
19	6-1-35-025	5.72E-05	517.52	40.45	28	406.10	11.75
20	6-2-35-025	5.70E-05	516.93	40.44	33	384.45	11.77
21	6-3-35-025	5.76E-05	523.43	41.05	30	364.19	12.02
22	6-4-50-025	5.66E-05	519.63	39.64	16	499.35	12.26
23	6-5-50-025	5.58E-05	529.39	39.64	17	513.54	11.90
24	6-6-50-025	5.68E-05	550.16	39.44	18	495.35	11.99
25	6-7-75-025	5.49E-05	531.19	41.65	6	726.51	12.44
26	6-8-75-025	5.59E-05	545.74	40.85	8	601.21	12.15
27	6-10-75-025	5.72E-05	525.52	44.71	5	662.27	12.64
28	9-2-35-025	5.70E-05	555.54	38.29	32	345.81	11.77
29	9-3-35-025	5.53E-05	535.77	38.64	30	389.87	12.31
30	9-4-50-025	5.59E-05	521.41	38.64	14	492.42	12.82
31	9-5-50-025	5.70E-05	519.24	36.49	12	543.31	12.57
32	9-6-50-025	5.71E-05	501.80	37.75	9	512.68	12.79
33	9-7-75-025	5.73E-05	532.64	37.75	5	669.88	12.89
34	9-8-75-025	5.63E-05	554.84	39.37	5	665.74	13.22
35	9-9-75-025	5.66E-05	540.52	37.56	5	666.34	12.96
36	9-10-35-025	5.69E-05	532.13	39.17	23	390.17	12.23

¼” Samples

Sample	Sample #	Volume (m^3)	Density (kg/m^3)	Application Rate (g/m^2/coat)	t_{ig} (s)	HRRPUA Peak (kW/m^2)	HOC Average (MJ/kg)
37	0-1-35-025-w	5.32E-05	524.85	n/a	53	232.18	11.43
38	0-2-35-025-w	5.51E-05	508.93	n/a	53	213.48	11.29
39	0-3-35-025-w	5.45E-05	460.00	n/a	39	225.41	11.06
40	0-4-50-025-w	5.41E-05	525.27	n/a	22	290.78	11.26
41	0-5-50-025-w	5.50E-05	483.86	n/a	23	297.69	11.67
42	0-6-50-025-w	5.43E-05	494.18	n/a	22	295.86	11.42
43	0-7-75-025-w	5.33E-05	477.51	n/a	13	308.82	11.28
44	0-8-75-025-w	5.58E-05	497.98	n/a	12	343.57	11.39
45	0-9-75-025-w	5.25E-05	501.19	n/a	12	363.88	11.15
46	3-1-35-025-w	5.50E-05	514.25	66.33	35	396.69	11.93
47	3-2-35-025-w	5.55E-05	484.31	61.78	41	420.73	12.10
48	3-3-35-025-w	5.43E-05	507.63	58.24	61	401.81	12.06
49	3-4-50-025-w	5.54E-05	485.33	55.00	18	374.54	10.73
50	3-5-50-025-w	5.44E-05	494.53	69.91	18	346.03	11.55
51	3-6-50-025-w	5.50E-05	496.79	71.18	16	457.34	11.54
52	3-7-75-025-w	5.65E-05	502.34	61.48	5	626.61	11.59
53	3-8-75-025-w	5.53E-05	506.10	62.78	6	---	---
54	3-9-75-025-w	5.58E-05	527.79	61.48	5	603.98	11.53
55	6-1-35-025-w	5.54E-05	521.87	56.09	28	393.68	11.91
56	6-2-35-025-w	5.61E-05	507.88	56.09	29	413.77	12.08
57	6-3-35-025-w	5.66E-05	569.67	50.15	29	462.77	11.97
58	6-4-50-025-w	5.76E-05	519.36	53.39	9	511.33	11.53
59	6-5-50-025-w	5.81E-05	551.82	49.91	15	534.09	12.15
60	6-6-50-025-w	5.77E-05	546.52	50.15	18	552.67	11.66
61	6-7-75-025-w	5.57E-05	531.43	53.93	5	760.56	11.87
62	6-8-75-025-w	5.63E-05	505.42	54.20	6	645.82	11.94
63	6-9-75-025-w	5.42E-05	573.27	54.73	5	640.30	11.88
64	9-1-35-025-w	5.44E-05	582.76	47.45	23	507.62	12.31
65	9-2-35-025-w	5.78E-05	555.09	44.32	24	361.73	11.72
66	9-3-35-025-w	5.77E-05	550.11	43.90	27	382.73	12.32
67	9-4-50-025-w	5.86E-05	550.84	46.38	14	519.57	12.15
68	9-5-50-025-w	5.77E-05	531.40	46.06	11	537.73	12.00
69	9-6-50-025-w	5.77E-05	562.06	47.69	12	463.31	12.61
70	9-7-75-025-w	5.51E-05	583.10	43.90	5	728.94	11.92
71	9-8-75-025-w	5.80E-05	525.30	47.15	6	743.54	12.03
72	9-9-75-025-w	5.42E-05	587.12	46.61	5	726.59	11.71

¼” Samples

Sample	Sample #	THR (MJ/m^2)	t_b (s)	b (dimensionless)	t_b/t_{ig}
1	0-1-35-025	23.4	212.00	1.29	5.30
2	0-2-35-025	23.8	269.00	1.44	6.40
3	0-3-35-025	20.8	211.00	1.26	5.41
4	0-4-50-025	25.6	226.00	2.45	9.83
5	0-5-50-025	24.2	236.00	2.42	11.24
6	0-6-50-025	23.2	196.00	2.42	10.32
7	0-7-75-025	27.2	159.00	3.15	11.36
8	0-8-75-025	27.0	177.00	3.35	11.80
9	0-9-75-025	28.5	193.00	3.61	13.79
10	3-1-35-025	25.0	243.00	2.61	6.57
11	3-2-35-025	22.7	260.00	2.78	7.88
12	3-3-35-025	24.1	266.00	2.86	6.82
13	3-4-50-025	25.8	188.00	3.99	11.75
14	3-5-50-025	29.1	246.00	4.11	12.30
15	3-6-50-025	27.2	214.00	3.70	8.92
16	3-7-75-025	---	---	---	---
17	3-8-75-025	31.6	227.00	4.59	16.21
18	3-9-75-025	29.4	180.00	4.77	18.00
19	6-1-35-025	26.6	265.00	2.96	9.46
20	6-2-35-025	26.8	254.00	2.71	7.70
21	6-3-35-025	29.0	273.00	2.53	9.10
22	6-4-50-025	31.0	252.00	3.93	15.75
23	6-5-50-025	29.4	232.00	4.06	13.65
24	6-6-50-025	32.4	243.00	3.88	13.50
25	6-7-75-025	32.4	208.00	6.24	34.67
26	6-8-75-025	31.6	202.00	4.97	25.25
27	6-10-75-025	35.0	221.00	5.60	44.20
28	9-2-35-025	29.2	244.00	2.33	7.63
29	9-3-35-025	28.3	251.00	2.78	8.37
30	9-4-50-025	31.7	246.00	3.87	17.57
31	9-5-50-025	32.2	241.00	4.38	20.08
32	9-6-50-025	31.7	251.00	4.09	27.89
33	9-7-75-025	35.6	202.00	5.67	40.40
34	9-8-75-025	25.3	234.00	5.64	46.80
35	9-9-75-025	36.2	226.00	5.64	45.20
36	9-10-35-025	27.7	235.00	2.80	10.22

¼” Samples

Sample	Sample #	THR (MJ/m^2)	t_b (s)	b (dimensionless)	t_b/t_{ig}
37	0-1-35-025-w	21.4	1090.00	1.27	20.57
38	0-2-35-025-w	24.2	1092.00	1.09	20.60
39	0-3-35-025-w	20.9	1138.00	1.22	29.18
40	0-4-50-025-w	28.0	895.00	1.88	40.68
41	0-5-50-025-w	27.2	962.00	1.95	41.83
42	0-6-50-025-w	24.4	966.00	1.94	43.91
43	0-7-75-025-w	25.7	648.00	2.07	49.85
44	0-8-75-025-w	26.3	644.00	2.42	53.67
45	0-9-75-025-w	26.4	776.00	2.62	64.67
46	3-1-35-025-w	28.6	1135.00	2.94	32.43
47	3-2-35-025-w	24.2	1125.00	3.17	27.44
48	3-3-35-025-w	23.9	1096.00	2.96	17.97
49	3-4-50-025-w	27.1	959.00	2.73	53.28
50	3-5-50-025-w	24.4	1007.00	2.44	55.94
51	3-6-50-025-w	28.0	954.00	3.56	59.63
52	3-7-75-025-w	29.4	665.00	5.26	133.00
53	3-8-75-025-w	32.8	746.00	---	124.33
54	3-9-75-025-w	32.5	717.00	5.03	143.40
55	6-1-35-025-w	29.4	1166.00	2.91	41.64
56	6-2-35-025-w	28.7	1136.00	3.11	39.17
57	6-3-35-025-w	33.1	1129.00	3.60	38.93
58	6-4-50-025-w	34.0	940.00	4.10	104.44
59	6-5-50-025-w	35.4	873.00	4.32	58.20
60	6-6-50-025-w	34.8	947.00	4.51	52.61
61	6-7-75-025-w	36.7	731.00	6.60	146.20
62	6-8-75-025-w	37.0	784.00	5.45	130.67
63	6-9-75-025-w	40.0	764.00	5.40	152.80
64	9-1-35-025-w	35.2	1141.00	4.06	49.61
65	9-2-35-025-w	34.7	1238.00	2.60	51.58
66	9-3-35-025-w	34.4	1204.00	2.80	44.59
67	9-4-50-025-w	37.8	996.00	4.18	71.14
68	9-5-50-025-w	37.5	900.00	4.37	81.82
69	9-6-50-025-w	40.2	988.00	3.62	82.33
70	9-7-75-025-w	40.2	697.00	6.28	139.40
71	9-8-75-025-w	39.1	714.00	6.43	119.00
72	9-9-75-025-w	38.6	730.00	6.26	146.00

¾” Samples

Sample	Sample #	Coats of PU	PU Type	q''_{ext} (kW/m^2)	m_{PU} (g)	m_{Total} (g)	Thickness (mm)	A_{Total} (cm^2)
1	0-1-35-075	0	oil	35	n/a	106.36	18.66	102.01
2	0-2-35-075	0	oil	35	n/a	101.86	18.77	101.51
3	0-3-35-075	0	oil	35	n/a	108.51	18.67	100.50
4	0-4-50-075	0	oil	50	n/a	102.95	18.75	100.00
5	0-5-50-075	0	oil	50	n/a	105.00	18.75	101.00
6	0-6-50-075	0	oil	50	n/a	104.41	18.75	100.50
7	0-7-75-075	0	oil	75	n/a	103.24	18.13	101.00
8	0-8-75-075	0	oil	75	n/a	107.67	18.47	101.51
9	0-9-75-075	0	oil	75	n/a	109.76	18.53	101.50
10	3-1-35-075	3	oil	35	1.55	106.70	18.54	101.50
11	3-2-35-075	3	oil	35	1.60	108.82	18.66	103.53
12	3-3-35-075	3	oil	35	1.70	104.99	18.33	102.52
13	3-4-50-075	3	oil	50	1.60	105.50	18.44	103.02
14	3-5-50-075	3	oil	50	1.55	109.08	18.62	102.01
15	3-6-50-075	3	oil	50	1.55	115.81	18.75	103.53
16	3-7-75-075	3	oil	75	1.65	107.10	18.71	102.52
17	3-8-75-075	3	oil	75	1.55	113.35	18.69	102.01
18	3-9-75-075	3	oil	75	1.35	108.12	18.74	101.50
19	6-1-35-075	6	oil	35	2.60	107.35	18.88	102.01
20	6-2-35-075	6	oil	35	2.60	110.02	18.85	101.50
21	6-3-35-075	6	oil	35	2.50	114.57	18.70	103.02
22	6-4-50-075	6	oil	50	2.45	108.38	18.90	102.01
23	6-5-50-075	6	oil	50	2.55	106.54	18.85	102.01
24	6-6-50-075	6	oil	50	2.60	105.18	18.73	101.51
25	6-7-75-075	6	oil	75	2.70	110.55	18.75	101.51
26	6-8-75-075	6	oil	75	2.55	106.68	18.80	100.50
27	6-9-75-075	6	oil	75	2.40	106.29	18.83	101.50
28	9-1-35-075	9	oil	35	3.80	112.64	18.67	103.02
29	9-2-35-075	9	oil	35	3.95	106.43	18.95	101.00
30	9-3-35-075	9	oil	35	4.00	107.08	18.45	100.00
31	9-4-50-075	9	oil	50	3.85	110.66	18.98	100.00
32	9-5-50-075	9	oil	50	3.70	107.82	18.91	100.00
33	9-6-50-075	9	oil	50	3.90	111.07	18.97	100.50
34	9-7-75-075	9	oil	75	3.80	111.10	18.85	102.52
35	9-8-75-075	9	oil	75	3.80	110.11	18.90	101.00
36	9-9-75-075	9	oil	75	3.45	105.68	18.74	101.00

¾” Samples

Sample	Sample #	Coats of PU	PU Type	q''_{ext} (kW/m^2)	m_{PU} (g)	m_{Total} (g)	Thickness (mm)	A_{Total} (cm^2)
37	0-1-35-075-w	0	water	35	n/a	107.23	18.44	102.01
38	0-2-35-075-w	0	water	35	n/a	107.74	18.31	103.02
39	0-3-35-075-w	0	water	35	n/a	105.58	18.15	103.02
40	0-4-50-075-w	0	water	50	n/a	104.90	18.20	102.52
41	0-5-50-075-w	0	water	50	n/a	105.96	18.53	102.01
42	0-6-50-075-w	0	water	50	n/a	107.60	18.10	102.51
43	0-7-75-075-w	0	water	75	n/a	103.10	18.00	103.53
44	0-8-75-075-w	0	water	75	n/a	102.75	18.13	103.53
45	0-9-75-075-w	0	water	75	n/a	113.72	18.25	103.02
46	3-1-35-075-w	3	water	35	2.05	105.87	18.58	104.04
47	3-2-35-075-w	3	water	35	1.90	104.86	18.13	103.02
48	3-3-35-075-w	3	water	35	1.90	105.42	18.72	101.51
49	3-4-50-075-w	3	water	50	1.85	111.58	18.76	102.52
50	3-5-50-075-w	3	water	50	1.85	109.92	18.58	103.02
51	3-6-50-075-w	3	water	50	2.15	106.60	18.65	102.01
52	3-7-75-075-w	3	water	75	2.15	102.71	18.63	103.53
53	3-8-75-075-w	3	water	75	2.00	105.22	18.65	103.53
54	3-9-75-075-w	3	water	75	1.70	110.13	18.62	102.52
55	6-1-35-075-w	6	water	35	3.15	107.00	18.70	102.52
56	6-2-35-075-w	6	water	35	3.25	109.48	18.51	103.02
57	6-3-35-075-w	6	water	35	2.90	108.39	18.17	103.53
58	6-4-50-075-w	6	water	50	3.00	111.92	18.46	102.52
59	6-5-50-075-w	6	water	50	3.05	108.30	18.61	103.53
60	6-6-50-075-w	6	water	50	3.30	109.96	18.75	103.53
61	6-7-75-075-w	6	water	75	3.40	109.81	18.70	102.52
62	6-8-75-075-w	6	water	75	3.35	109.66	18.76	102.52
63	6-9-75-075-w	6	water	75	3.15	107.15	18.64	102.52
64	9-1-35-075-w	9	water	35	4.35	107.03	18.38	102.01
65	9-2-35-075-w	9	water	35	4.40	106.35	18.88	102.51
66	9-3-35-075-w	9	water	35	4.45	110.20	19.18	102.51
67	9-4-50-075-w	9	water	50	4.15	112.56	18.94	103.02
68	9-5-50-075-w	9	water	50	4.45	108.26	18.71	102.01
69	9-6-50-075-w	9	water	50	4.45	106.82	18.64	102.52
70	9-7-75-075-w	9	water	75	4.35	108.95	18.46	105.06
71	9-8-75-075-w	9	water	75	4.35	105.47	18.86	103.53
72	9-9-75-075-w	9	water	75	4.70	107.60	18.79	103.53

¾” Samples

Sample	Sample #	Volume (m^3)	Density (kg/m^3)	Application Rate (g/m^2/coat)	t_{ig} (s)	HRRPUA Peak (kW/m^2)	HOC Average (MJ/kg)
1	0-1-35-075	1.90E-04	558.76	n/a	46	246.57	12.22
2	0-2-35-075	1.91E-04	534.63	n/a	43	226.94	11.86
3	0-3-35-075	1.88E-04	578.31	n/a	52	249.31	11.90
4	0-4-50-075	1.88E-04	549.07	n/a	26	271.36	11.78
5	0-5-50-075	1.89E-04	554.46	n/a	25	282.85	11.74
6	0-6-50-075	1.88E-04	554.08	n/a	27	313.68	12.22
7	0-7-75-075	1.83E-04	563.80	n/a	12	355.81	11.79
8	0-8-75-075	1.87E-04	574.30	n/a	13	328.83	11.80
9	0-9-75-075	1.88E-04	583.58	n/a	13	380.51	11.76
10	3-1-35-075	1.88E-04	567.01	50.90	44	272.41	11.92
11	3-2-35-075	1.93E-04	563.29	51.51	39	319.17	11.89
12	3-3-35-075	1.88E-04	558.72	55.28	69	326.82	11.74
13	3-4-50-075	1.90E-04	555.34	51.77	21	365.38	11.21
14	3-5-50-075	1.90E-04	574.29	50.65	18	372.76	11.20
15	3-6-50-075	1.94E-04	596.59	49.91	19	376.75	11.37
16	3-7-75-075	1.92E-04	558.38	53.65	---	---	---
17	3-8-75-075	1.91E-04	594.52	50.65	9	463.07	11.72
18	3-9-75-075	1.90E-04	568.42	44.33	11	418.47	11.51
19	6-1-35-075	1.93E-04	557.40	42.48	36	302.93	11.81
20	6-2-35-075	1.91E-04	575.03	42.69	31	344.51	11.71
21	6-3-35-075	1.93E-04	594.71	40.45	37	378.47	11.30
22	6-4-50-075	1.93E-04	562.14	40.03	14	434.02	11.97
23	6-5-50-075	1.92E-04	554.06	41.66	16	391.01	11.82
24	6-6-50-075	1.90E-04	553.23	42.69	13	385.17	11.40
25	6-7-75-075	1.90E-04	580.86	44.33	5	529.48	11.82
26	6-8-75-075	1.89E-04	564.62	42.29	6	554.13	11.86
27	6-9-75-075	1.91E-04	556.13	39.41	5	547.85	12.05
28	9-1-35-075	1.92E-04	585.63	40.98	43	354.93	11.88
29	9-2-35-075	1.91E-04	556.08	43.45	34	395.56	12.40
30	9-3-35-075	1.85E-04	580.38	44.44	32	362.48	11.85
31	9-4-50-075	1.90E-04	583.03	42.78	15	458.59	12.12
32	9-5-50-075	1.89E-04	570.17	41.11	12	473.96	12.30
33	9-6-50-075	1.91E-04	582.59	43.12	15	486.68	11.91
34	9-7-75-075	1.93E-04	574.93	41.19	5	574.44	11.90
35	9-8-75-075	1.91E-04	576.82	41.80	5	510.09	12.01
36	9-9-75-075	1.89E-04	558.34	37.95	4	551.80	11.93

¾” Samples

Sample	Sample #	Volume (m^3)	Density (kg/m^3)	Application Rate (g/m^2/coat)	t_{ig} (s)	HRRPUA Peak (kW/m^2)	HOC Average (MJ/kg)
37	0-1-35-075-w	1.88E-04	570.06	n/a	49	295.02	---
38	0-2-35-075-w	1.89E-04	571.16	n/a	45	257.01	---
39	0-3-35-075-w	1.87E-04	564.64	n/a	44	300.24	11.06
40	0-4-50-075-w	1.87E-04	562.23	n/a	26	344.35	11.93
41	0-5-50-075-w	1.89E-04	560.58	n/a	21	349.93	11.66
42	0-6-50-075-w	1.86E-04	579.92	n/a	26	353.42	10.96
43	0-7-75-075-w	1.86E-04	553.25	n/a	10	446.61	11.43
44	0-8-75-075-w	1.88E-04	547.42	n/a	13	448.32	11.11
45	0-9-75-075-w	1.88E-04	604.84	n/a	13	418.01	11.29
46	3-1-35-075-w	1.93E-04	547.69	65.68	40	440.54	11.77
47	3-2-35-075-w	1.87E-04	561.41	61.48	35	567.34	11.99
48	3-3-35-075-w	1.90E-04	554.79	62.39	39	601.87	11.10
49	3-4-50-075-w	1.92E-04	580.18	60.15	14	547.89	12.14
50	3-5-50-075-w	1.91E-04	574.26	59.86	10	603.82	12.93
51	3-6-50-075-w	1.90E-04	560.33	70.26	9	603.01	12.85
52	3-7-75-075-w	1.93E-04	532.52	69.22	5	711.52	12.26
53	3-8-75-075-w	1.93E-04	544.95	64.39	6	742.34	12.87
54	3-9-75-075-w	1.91E-04	576.95	55.28	5	747.56	12.40
55	6-1-35-075-w	1.92E-04	558.15	51.21	31	489.22	13.16
56	6-2-35-075-w	1.91E-04	574.11	52.58	25	503.58	13.36
57	6-3-35-075-w	1.88E-04	576.19	46.69	30	468.71	12.52
58	6-4-50-075-w	1.89E-04	591.41	48.77	11	643.04	12.96
59	6-5-50-075-w	1.93E-04	562.10	49.10	13	590.80	12.79
60	6-6-50-075-w	1.94E-04	566.46	53.12	10	594.08	13.10
61	6-7-75-075-w	1.92E-04	572.81	55.28	4	845.82	13.64
62	6-8-75-075-w	1.92E-04	570.20	54.46	4	883.45	14.12
63	6-9-75-075-w	1.91E-04	560.74	51.21	4	699.45	13.81
64	9-1-35-075-w	1.87E-04	570.86	47.38	30	428.66	13.36
65	9-2-35-075-w	1.94E-04	549.50	47.69	21	437.80	13.39
66	9-3-35-075-w	1.97E-04	560.49	48.23	26	505.13	13.23
67	9-4-50-075-w	1.95E-04	576.86	44.76	14	572.31	13.44
68	9-5-50-075-w	1.91E-04	567.23	48.47	14	612.38	13.77
69	9-6-50-075-w	1.91E-04	559.01	48.23	11	610.14	13.92
70	9-7-75-075-w	1.94E-04	561.77	46.01	8	843.00	13.92
71	9-8-75-075-w	1.95E-04	540.16	46.69	5	811.36	13.88
72	9-9-75-075-w	1.95E-04	553.12	50.44	6	851.95	13.84

¾” Samples

Sample	Sample #	THR (MJ/m^2)	t_b (s)	b (dimensionless)	t_b/t_{ig}
1	0-1-35-075	115.3	1191.00	1.43	25.89
2	0-2-35-075	105.9	1123.00	1.23	26.12
3	0-3-35-075	115.1	1118.00	1.45	21.50
4	0-4-50-075	109.1	963.00	1.69	37.04
5	0-5-50-075	110.2	915.00	1.80	36.60
6	0-6-50-075	116.6	936.00	2.11	34.67
7	0-7-75-075	111.5	687.00	2.54	57.25
8	0-8-75-075	116.5	690.00	2.27	53.08
9	0-9-75-075	118.3	736.00	2.79	56.62
10	3-1-35-075	113.4	1249.00	1.69	28.39
11	3-2-35-075	114.1	1334.00	2.16	34.21
12	3-3-35-075	106.1	1068.00	2.20	15.48
13	3-4-50-075	105.3	913.00	2.63	43.48
14	3-5-50-075	108.4	970.00	2.71	53.89
15	3-6-50-075	117.9	1033.00	2.75	54.37
16	3-7-75-075	---	---	---	---
17	3-8-75-075	120.4	741.00	3.62	82.33
18	3-9-75-075	113.5	706.00	3.17	64.18
19	6-1-35-075	112.4	1266.00	2.00	35.17
20	6-2-35-075	114.1	1380.00	2.42	44.52
21	6-3-35-075	113.9	1375.00	2.76	37.16
22	6-4-50-075	116.9	962.00	3.33	68.71
23	6-5-50-075	110.5	928.00	2.89	58.00
24	6-6-50-075	106.3	921.00	2.84	70.85
25	6-7-75-075	118.8	731.00	4.29	146.20
26	6-8-75-075	116.2	700.00	4.53	116.67
27	6-9-75-075	117.6	735.00	4.47	147.00
28	9-1-35-075	116.4	1181.00	2.51	27.47
29	9-2-35-075	113.4	1158.00	2.93	34.06
30	9-3-35-075	111.9	1194.00	2.60	37.31
31	9-4-50-075	119.5	965.00	3.57	64.33
32	9-5-50-075	119.6	939.00	3.73	78.25
33	9-6-50-075	116.9	984.00	3.85	65.60
34	9-7-75-075	117.3	726.00	4.74	145.20
35	9-8-75-075	122.0	762.00	4.09	152.40
36	9-9-75-075	114.2	691.00	4.51	172.75

¾” Samples

Sample	Sample #	THR (MJ/m^2)	t_b (s)	b (dimensionless)	t_b/t_{ig}
37	0-1-35-075-w	106.7	240.00	1.75	4.90
38	0-2-35-075-w	103.7	271.00	1.40	6.02
39	0-3-35-075-w	101.9	234.00	1.81	5.32
40	0-4-50-075-w	106.1	230.00	2.33	8.85
41	0-5-50-075-w	110.8	263.00	2.42	12.52
42	0-6-50-075-w	110.6	218.00	2.41	8.38
43	0-7-75-075-w	106.8	175.00	3.41	17.50
44	0-8-75-075-w	107.3	169.00	3.41	13.00
45	0-9-75-075-w	115.9	200.00	3.12	15.38
46	3-1-35-075-w	112.8	276.00	3.26	6.90
47	3-2-35-075-w	112.7	231.00	4.52	6.60
48	3-3-35-075-w	110.2	238.00	4.85	6.10
49	3-4-50-075-w	108.3	222.00	4.42	15.86
50	3-5-50-075-w	114.6	223.00	4.99	22.30
51	3-6-50-075-w	110.8	228.00	4.99	25.33
52	3-7-75-075-w	107.8	183.00	6.09	36.60
53	3-8-75-075-w	---	226.00	6.40	37.67
54	3-9-75-075-w	116.1	209.00	6.45	41.80
55	6-1-35-075-w	112.0	256.00	3.77	8.26
56	6-2-35-075-w	115.7	223.00	3.92	8.92
57	6-3-35-075-w	114.3	260.00	3.57	8.67
58	6-4-50-075-w	116.2	274.00	5.39	24.91
59	6-5-50-075-w	119.1	248.00	4.86	19.08
60	6-6-50-075-w	114.8	266.00	4.90	26.60
61	6-7-75-075-w	119.7	233.00	7.44	58.25
62	6-8-75-075-w	121.2	232.00	7.82	58.00
63	6-9-75-075-w	118.0	254.00	5.98	63.50
64	9-1-35-075-w	115.8	288.00	3.18	9.60
65	9-2-35-075-w	110.2	293.00	3.31	13.95
66	9-3-35-075-w	123.1	284.00	3.96	10.92
67	9-4-50-075-w	124.3	254.00	4.67	18.14
68	9-5-50-075-w	118.7	283.00	5.07	20.21
69	9-6-50-075-w	123.1	290.00	5.06	26.36
70	9-7-75-075-w	120.2	239.00	7.40	29.88
71	9-8-75-075-w	116.4	237.00	7.09	47.40
72	9-9-75-075-w	115.2	188.00	7.49	31.33

Appendix E – Thermal Inertia Data

							No Heat Loss $\dot{q}''_{inc}$			Tewarson $\dot{q}''_{net}$		
		q =	35 kW/m^2	50 kW/m^2	75 kW/m^2		35 kW/m^2	50 kW/m^2	75 kW/m^2	35 kW/m^2	50 kW/m^2	75 kW/m^2
Thickness in.	Coats PU	PU Type	Avg. tig (s)	Avg. tig (s)	Avg. tig (s)	Avg. Tig (^{o}C)	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s	$(k\rho c)_{eff}$ (kW/m^{2}K)^2 s
1/4	0	n/a	44	22	13	255	1.25	1.24	1.72	0.41	0.61	1.10
1/4	3	oil	36	20	13	273	0.88	0.99	1.41	0.29	0.49	0.90
1/4	6	oil	30	17	6	303	0.59	0.68	0.57	0.19	0.33	0.36
1/4	9	oil	28	12	5	249	0.84	0.71	0.68	0.28	0.35	0.44
1/4	3	water	46	17	5	303	0.89	0.69	0.48	0.29	0.34	0.30
1/4	6	water	29	14	5	278	0.67	0.67	0.57	0.22	0.33	0.37
1/4	9	water	25	12	5	265	0.64	0.66	0.64	0.21	0.32	0.41
3/4	0	n/a	47	25	12	319	0.81	0.90	0.99	0.27	0.44	0.63
3/4	3	oil	51	19	10	281	1.16	0.90	1.05	0.38	0.44	0.67
3/4	6	oil	35	14	5	270	0.87	0.73	0.61	0.29	0.36	0.39
3/4	9	oil	36	14	5	261	0.98	0.77	0.58	0.32	0.38	0.37
3/4	3	water	38	11	5	301	0.75	0.44	0.48	0.25	0.22	0.31
3/4	6	water	29	11	4	285	0.64	0.51	0.41	0.21	0.25	0.26
3/4	9	water	26	13	6	273	0.62	0.64	0.71	0.21	0.32	0.45

REFERENCES

1. Belles, Donald W., "Interior Finish," Section 12/Chapter 3, Fire Protection Handbook, 19th Edition, National Fire Protection Agency, Quincy, MA, 2003.

2. ASTM E1354 – 02a, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, American Society for Testing and Materials, West Conshohocken, PA, 2002.

3. ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, American Society for Testing and Materials, W. Conshohocken, PA, 1994.

4. McGraw, J.R. Jr., Mowrer, F.W., "Flammability of Painted Gypsum Wallboard Subjected to Fire Heat Fluxes," Proc. – Interflam 1999, Vol. 2, Interscience Communications Ltd., London, 1999.

5. Mowrer, F.W. "The Effect of 'Blistering' on the Ignition Time and Flammability of Painted Gypsum Wallboard," Proc. – *Fire and Materials*, San Francisco, 2001.

6. Dreisbach, Jason, "Flammability Characteristics of Painted Concrete Blocks," NIST GCR 02-832, April 2002.

7. McGraw, J. R., Jr.; Mowrer, F. W. "Flammability and Dehydration of Painted Gypsum Wallboard Subjected to Fire Heat Fluxes" *Fire Safety Science – Proceedings. Sixth (6th) International Symposium*, International Association for Fire Safety Science (IAFSS). July 5-9, 1999, Poitiers, France, Intl. Assoc. for Fire Safety Science, Boston, MA, Curtat, M., Editor(s), 1003-1014 pp, 2000.

8. Mowrer, Frederick W., "An Analysis of Effective Thermal Properties of Thermally Thick Materials," NIST GCR 03-855, July 2003.

9. Harada, Toshiro, "Time to Ignition, Heat Release Rate and Fire Endurance Time of Wood in Cone Calorimeter Test," *Fire and Materials*, Vol. 25, pp. 161-167, 2001.

10. National Astronomical Observatory. Chronological Scientific Tables (Rika nenpyo), Maruzen, Tokyo, 1992; 1040.

11. Spearpoint, M. J., Quintiere, J. G. "Predicting the piloted ignition of wood in the Cone Calorimeter Using an Integral Model – Effect of Species, Grain Orientation and Heat Flux," Fire Safety Journal, Vol. 36, pp. 391-415, 2001.

12. Atreya, A., Abu-Zaid, M., "Effect of Environmental Variables on Piloted Ignition," *Fire Safety Science – Proceedings of the Second International Symposium,* pp. 177-86, 1989.

13. ASTM E1321-03, *Standard Method for Determining Material Ignition and Flame Spread Properties*, American Society for Testing and Materials, West Conshohocken, PA, 2003.

14. Long, R.T., Jr., Torero, J.L., Quintiere, J.G., and Fernandez-Pello, A.C. "Scale and Transport Considerations on Piloted Ignition of PMMA," *Fire Safety Science – Proceedings of the 6th International Symposium*, International Association for Fire Safety Science, 2000.

15. Cleary, T. G., "Flammability Characterization With the LIFT Apparatus and the Cone Calorimeter," Fire Retardant Chemicals Association. Technical and Marketing Issues Impacting the Fire Safety of Building and Construction and Home Furnishings Applications, Technomic Publishing Co., Lancaster, PA, pp. 99-115, 1992.

16. Mowrer, F.W., Williamson, R.B., "Flame Spread Evaluation for Thin Interior Finish Materials," *Fire Safety Science – Proceedings of the Third (3rd) International Symposium*, eds. G. Cox and B. Langford, Elsevier, London, 1991.

17. Belles, Donald W., "Interior Finish," Section 12/Chapter 3, Fire Protection Handbook, 19th Edition, National Fire Protection Agency, Quincy, MA, 2003.

18. The SFPE Handbook of Fire Protection Engineering, 3rd Edition, National Fire Protection Agency, Quincy, MA, 2002.

19. Babrauskas, Vytenis, "Common Solids," *SFPE Ignition Handbook*, pp. 257-264, 2003.

20. Saito, K., Quintiere, J.G., and Williams, F.A., "Upward Turbulent Flame Spread," *Fire Safety Science - Proceedings of the First (1st) International Symposium,* eds. C.E. Grant and P.J. Pagni, Hemisphere, Washington, DC, 1986.

21. Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," Section 3/ Chapter 4, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, National Fire Protection Association, Quincy, MA, 2002.

22. Urbas, Joe, “Effects of Retainer Frame, Irradiance Level and Specimen Thickness on Cone Calorimeter Test Results,” *Fire and Materials*, John Wiley and Sons, Ltd. 2004.

23. Fangrat, J., Hasemi, Y., Masashi, Y., and Kikuchi, S., “Relationship Between Heat of Combustion, Lignin Content and Burning Weight Loss,” *Fire and Materials*, Vol. 22, pp. 1-6, 1998.